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GEOLOGY OF THE ORE DEPOSITS OF KENNECOTT, ALASKA.

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CONTENTS.

	PAGE.
INTRODUCTION	2
TOPOGRAPHY	4
ROCK FORMATIONS	5
STRUCTURE	10
PHYSIOGRAPHIC DEVELOPMENT	14
ORE DEPOSITS	17
General	17
Character of ore	18
Types of deposits	18
Mineralization in greenstone	19
Mineralization in limestone	20
Talus ore deposit	23
Glacier ore deposit	23
Structural relations	24
Relation of mineralization to rocks	24
Behavior of fissures	26
Relation of mineralization to fractures	27
Relation of mineralization to folds	29
Relation of mineralization to faults	30
Shapes and sizes of ore bodies	30
Relation to surface	31

[1] This paper embodies the results of field and laboratory studies of the Kennecott deposits carried on at various times during the last five years. The authors were together at Kennecott in the field season of 1915, when the work was initiated in coöperation with the Secondary Enrichment Investigation. Field work was continued by the first named author during the four following seasons in his capacity of consulting geologist to the Kennecott Copper Corporation, while most of the detailed microscopic work was done in the laboratory by the other, in connection with research for the Secondary Enrichment Investigation.

Distribution of ore bodies 33
Alteration of host rocks 34
Mineralogy and mineralography 35
OXIDATION OF ORE DEPOSITS 44
General 44
Minerals due to oxidation 45
Distribution and depth of oxidation 48
Relation of oxidation to structures 49
Relation to water level and climate 50
Age of oxidation 53
THEORETICAL CONSIDERATIONS 54
Origin of fissures 54
Suggested hypothesis 54
Origin of mineralization 57
Source of metals in limestone 57
Origin of copper in greenstone 59
Agents of transportation 61
Methods of deposition 65
Primary or secondary origin of the chalcocite 66
Experimental evidence 67
Mineralographic evidence 67
Field evidence 70
Discussion of evidence 73
Conclusions 77
SUMMARIZED CONCLUSION OF ORIGIN OF ORE DEPOSITS 77

INTRODUCTION.

General.—The copper deposits of the famous Bonanza and Jumbo Mines at Kennecott, Alaska, are unique for the character of their ores and their purity and size. Their occurrence presents many peculiar and interesting features, and the origin of the great masses of chalcocite has long been a puzzle. Their deciphering involves the origin of fractures unusual in form; of a peculiar kind of primary mineralization unparalleled in other deposits; of a source of metals not customarily considered, as well as agents of transportation but seldom referred to. No conclusions can be reached without carefully weighing the primary or secondary origin of the chalcocite, and much of interest is gained regarding the distribution of oxidation and groundwater. It is with these problems that the paper deals, and the facts and conclusions presented in the following pages are the result of a study extending over a period of five seasons, during which time the development of the ore bodies has been carefully followed and their details accurately mapped.

Location.—The Bonanza and Jumbo Mines, the most impor-

tant of the mining properties of the Kennecott Copper Corp., are situated at Kennecott, Alaska. (See Fig. 1.) This town lies about 200 miles northeast of the port of Cordova, on Prince William Sound, with which it is connected by the Copper River and Northwestern Railroad, a road which winds around glaciers and is famous for the difficulties of its construction. The Port of

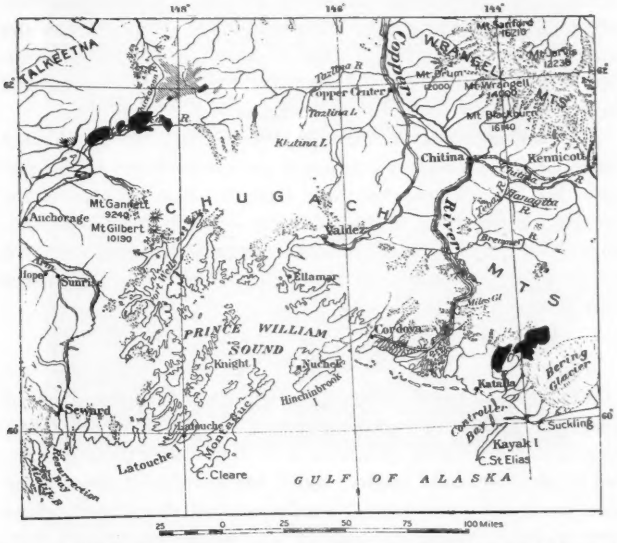


FIG. 1. Index map to show location of Cordova, Copper River and Kennecott.

Cordova is navigable the year around and the railroad maintains continuous service with Kennecott, suffering only slight interruption, inevitable with its location.

The mines are one mile apart and each one is at a distance of three miles from the town of Kennecott[2] and 4,000 feet above it, at an elevation of about 6,000 feet. They are connected with the mill in the town by aërial tramways.

[2] The U. S. Geol. Surv. terminology gives the spelling as Kennicott but the post office and company name are spelt as Kennecott. As the latter is common usage it is followed in this paper.

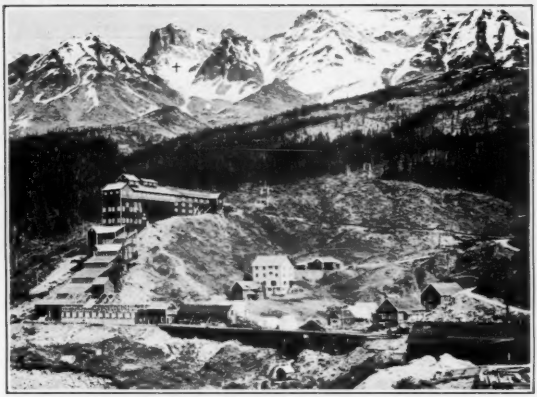
Acknowledgments.—We take pleasure in acknowledging the courtesies and help rendered by the staff at Kennecott in 1915, and the aid received from the geologic maps prepared by W. E. Dunkle and H. D. Smith. The first named writer further records with appreciation the benefit received in the seasons since 1915 from discussions with E. T. Stannard, Wm. Douglas, H. D. Smith, D. C. Hoyt, and D. D. Irwin, and the helpfulness of their information concerning the detailed development of the ore bodies. Acknowledgment is due to Mr. Stephen Birch, president of the company, for placing all facilities at our disposal and for his permission to publish this material.

The painstaking areal work by the members of the United States Geological Survey facilitated our observations and deductions, and we acknowledge more than the mere sources of the information recorded to the individual members in the footnotes. To Professor L. C. Graton we especially desire to record our grateful thanks for his many discussions and sympathetic criticisms.

TOPOGRAPHY.

The region in the vicinity of the mines is one of pronounced relief with high, steep-sided mountains, rugged in detail, rising from Kennecott Valley (Plate I., *A*). The valley itself is occupied by the Kennecott glacier, which has a width of about three miles at the town and extends northwestward about twenty-four miles to its gathering grounds on Mt. Blackburn, 16,140 feet, and Mt. Regal, about 14,000 (Plate I., *B*).

The mountain sides on the Kennecott edge of the glacier rise steeply to the sharp divide of Kennecott spur at an elevation of about 7,000 feet. The Spur juts southward from the main Wrangel Mountains and is limited on the west by Kennecott Valley and on the east by McCarthy Creek, and rises from an elevation of 2,000 feet at the glacier and 2,650 feet at McCarthy Creek, to nearly 7,000 feet (Fig. 3). The top of the divide where occupied by the Chitistone limestone is serrated into perpendicular pinnacles and hoodoo forms of the shattered brittle



a.

b.

c.

a. Kennecott spur and town of Kennecott, showing topography and location of mines (+).

b. Kennecott glacier. Mt. Blackburn in background and greenstone-limestone contact at right.

c. "Hoodoo" topography developed on fractured limestone adjacent to Bonanza Mine.

a.

b.

c.

a. Contact between greenstone (dark) and limestone (light). Jumbo Mine at right.

b. Greenstone-limestone contact. Normal contact at left, down-faulted against greenstone.

c. Quartz-diorite porphyry with inclusions of black shale of Kennecott formation.

rock, resembling the Dolomite Alps (Plate I., *C*). Great talus slopes, at the angle of repose, reach down hundreds of feet below the pinnacles. The lower slopes underlain by the greenstone, are less rough, with occasional benches and cliffs. The areas of porphyry weather to smooth steep slopes covered by talus.

The mines lie approximately 1,000 feet below the highest point of the spur. The slopes are scored by deep, steep-sided, V-shaped tributary gulches containing dashing streamlets which empty into the main valley at the edge of the glacier. The heads of these gulches contain small hanging glaciers, rock glaciers,[3] or talus slopes. The Jumbo Mine is situated in a basin at the edge of one of these glaciers (Plate II., *A*) and the Bonanza ore body outcrops along the sharp crest of a narrow transverse spur lying between two such basins.

On the McCarthy Creek side of the divide, part way down the slope, lies the Mother Lode Mine.

ROCK FORMATIONS.

The formations in the vicinity of Kennecott are tabularly shown as follows.[4] (See also Fig. 2.)

Quaternary	Alluvium.	Flood plain gravels, sands and silts.
	Rock glaciers.	Broken rock and ice.
	Moraines.	Glacial till—partly sorted.
Jurassic or later.	Quartz-diorite porphyry.	Stocks, dikes and sills.
Upper Jurassic.	Kennecott formation.	Shales, sandstones, and conglomerate.
Upper Triassic	McCarthy shale.	Shale with few thin-bedded limestones.
	Chitistone limestone.	Massive limestone, mostly magnesian, ore-containing.
Triassic.	Nikolai greenstone.	Altered basaltic lava flows.

[3] Rock glaciers (see Moffit and Capps, Bull. 448, U. S. Geol. Surv.) are mixtures of rock and ice, or rather frozen talus slopes. They exhibit the characteristics of glaciers in their movements.

[4] The formation names and geologic ages are taken from: U. S. Geol. Surv. Bull. 662, p. 164, 1918, by Fred H. Moffit, and Bull. 448, 1911, by F. H. Moffit and S. R. Capps.

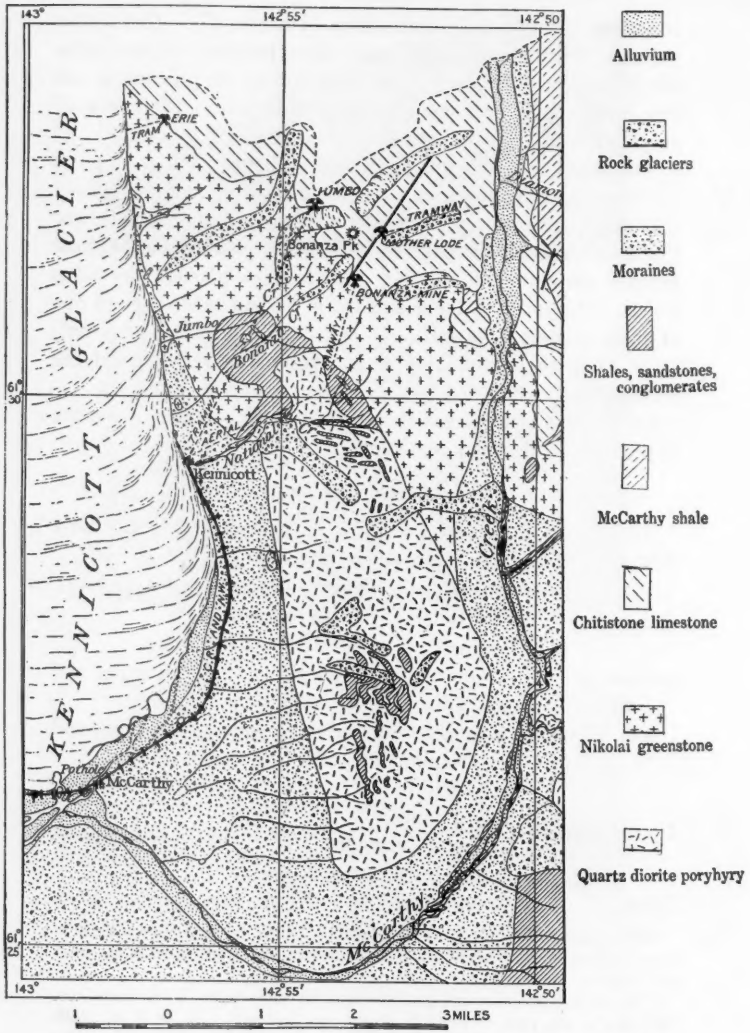


FIG. 2. Sketch map of geology, vicinity of Kennecott, U. S. G. S. Bull. 622.

Nikoli Greenstone.—The Nikoli greenstone appears to be a regular and massively bedded, sedimentary series with certain harder beds expressed in abrupt cliffs and softer ones in benches. It is, however, a succession of altered basaltic lava flows, each flow varying slightly in composition and ranging from about 25 to 100 feet in thickness. The total thickness exposed in the vicinity of the mines is at least 3,500 feet, and the base cannot be seen. Elsewhere it is estimated to have a thickness of 4,000 to 5,000 feet.[5]

The formation is widespread, extending as a narrow belt several tens of miles on either side of Kennecott. Its upper contact with the conformably overlying Chitistone limestone is the most distinctive geologic feature of the district and can be traced by the eye over wide areas (Plate II., *A, B*). It is, therefore, older than the upper Triassic Chitistone limestone, and Moffit and Capps[6] consider it of probably early Triassic age.

With close inspection some beds are seen to consist of dense, hard greenish gray lavas, and others of softer reddish or greenish colored lavas. The texture varies from dense to medium grained porphyritic. Both varieties may be amygdaloidal, but the reddish variety is notably so. Some beds are not amygdaloidal, and others may contain the amygdules at one place but not at any other along the strike. The amygdules are, however, fairly equally distributed vertically, within one bed, and not concentrated at the top of the individual flows as in the Lake Superior amygdaloids, though there is a suggestion, in places, of a gradation from dense to amygdaloidal toward the top of a flow. The fillings consist of chlorites, serpentine, chalcedony and opal, calcite, laumontite, thompsonite, quartz and epidote. Specks of native copper, chalcocite, bornite, and chalcopyrite have also been observed in the amygdules. The beds are traversed by numerous joint planes and occasional veinlets of quartz and epidote.

Microscopically the rocks are seen to be basaltic in composition

[5] Moffit, F. H., and Capps, S. R., U. S. Geol. Surv. Bull. 448, 1911, p. 62.
[6] *Op. cit.*, p. 63.

with pronounced ophitic texture which persists even where the rock is amygdaloidal. They are invariably altered and now contain considerable serpentine, chlorite, calcite, and epidote, and extremely small amounts of zeolites. Some of the reddish varieties seem to owe their color to the presence of minute scales of iddingsite, as a result of alteration from olivine.

Chitistone Limestone.—The Chitistone formation is of especial interest because the valuable copper deposits of the district are localized in it. It is a conspicuous, heavy-bedded formation, widely distributed throughout the Kennecott region. It is intersected by several systems of fracturing which have divided it into a series of polygonal blocks. These permitted frost erosion to proceed with unusual rapidity so that on the hills abrupt cliffs and prominent hoodoo pinnacles form a rugged outline (Plate *I.*, C, II., *B*). The formation rests on the Nikolai greenstone and is conformably overlain by the McCarthy shale.

In its type locality the thickness of the Chitistone is 3,000 feet,[7] but near Kennecott is considerably less. The lower part of the formation consists of a 4–7 foot bed of shale, the lower part of which is red and the upper part green. Where it is exposed in the mines it is slickenslided and crumpled and often locally thinned or thickened, giving evidence of movement along it. Although thin, this shale bed is an important feature of the district, because it weathers to a prominent bench and often forms the only mode of travel along a line of difficult cliffs. Above the shale is 12 feet of thin-bedded, smooth, hard, gray, argillaceous limestone, then 23 feet of thin-bedded, rough, pebbly limestone containing flattened, cylindrical, fossil-like grains, and 30 feet or more of dull, dark-gray limestone in thicker beds. The remainder of the formation consists of massive beds of sparkling light gray dolomitic limestone with occasional beds of darker rock. The dolomitic beds are notably shattered and contain numerous seams of calcite. The upper part of the Chitistone limestone becomes thinner bedded and shaly, and grades almost insensibly into the overlying McCarthy shales.

[7] *Op. cit.*, p. 23.

The gray limestone is fairly pure, yielding 3.9 per cent. $MgCO_3$, whereas the sparkling gray dolomite rock averages about 30 per cent. $MgCO_3$. The dolomitization was not connected with the immediate ore deposition, for it is a widespread feature, neither is it a stratigraphic phase, for the contact between the dolomite and gray limestone is an irregular surface, in some places cutting across bedding planes, following them in others, or terminating abruptly against small faults along or normal to the bedding planes.

McCarthy Shale.—This formation, of upper Triassic age, with its basal shale-limestone transition zone, has a probable thickness of at least 3,000 feet. Its top is not exposed.[8] It occurs in the vicinity of the mines, but bears no relation to the ore deposits, nor is it known to contain valuable minerals.

Kennecott Formation.—This formation, consisting of conglomerates, sandstone, and gray and black shales, with a thickness of probably more than 7,500 feet, rests unconformably upon all of the three earlier formations. Moffit[9] considers it to be of Upper Jurassic age. It does not occur in the immediate vicinity of the mines and bears no relation to the ore deposits. With the exception of the Quaternary gravels this formation completes the sedimentary series near the mines.

Porphyries.—Light colored quartz-diorite porphyries intrude the greenstone and all of the sedimentary rocks, in the form of stocks, dikes, and sills. They occur most abundantly about one mile from the Bonanza Mine, where they form a large stock which constitutes Porphyry Mountain. This intrusion contains numerous large inclusions of black shale, presumably of the Kennecott formation (Plate II., *C*). The edges of the inclusions are sharp and the adjacent porphyry shows no evidence of assimilation. The shale masses probably represent blocks of the cover engulfed in the porphyry by the process of magmatic stoping.

Porphyry is strikingly absent in the immediate vicinity of the

[8] *Op. cit.*, 29.

[9] Moffit, F. H., U. S. Geol. Surv. Bull. 542, p. 82, 1913.

ore deposits, but one dike was observed cutting the Chitistone limestone about 1,000 feet from the Jumbo Mine, and another two-foot dike cuts the limestone and the copper vein in the Erie prospect.

The porphyry consists of phenocrysts of quartz and andesine with small biotites and hornblende, embedded in a microgranitic (or rarely glassy) groundmass. Alteration products are practically always present. The universally fine-grained character of the intrusive suggests intrusion under light cover. No contact metamorphism has been found around the margins of the intrusive in the Kennecott section and no metalliferous deposits are known to occur in it. The relation the porphyry may bear to the copper deposits at Kennecott will be discussed later.

STRUCTURE.

The major structural features of the greenstone, Chitistone limestone and McCarthy shale are almost identical, except that the last has been crumpled more than the more resistant older formations. The Chitistone limestone and the greenstone are the formations whose structure need be considered in detail. The contact between the two (Plate II., *A*), accentuated by their strong color contrast, forms the datum plane from which the larger structural features may be worked out.

Folds.—The mines are on the northeast flank of a broad anticlinal fold whose axis pitches gently northwesterly. Part of the southwest limb occurs on the southwest side of Kennecott Valley; the central part is occupied by the valley, and the northeast limb, now dissected into rugged mountains, contains the mines (Fig. 3). Thus the greenstone and Chitistone limestone in the vicinity of the mines have a northwesterly strike and a dip of from 23 to 30° N.E. (Fig. 2). Several small open folds lie on the northern flank of the main anticline with their axes at right angles to the main one and pitching parallel to the dip of the beds forming the major anticline. This causes a fluting of flat troughs and flat ridges up and down the beds comprising the flank of the anticline, like slickenslides on the surface of a flatly dipping

fault. The major anticline can be clearly seen from any height by following the greenstone-limestone contact along the bare upper slopes, but the minor crossfolds are not casually evident because of the steep and broken topography. They become known only by careful study. A structure contour map of the

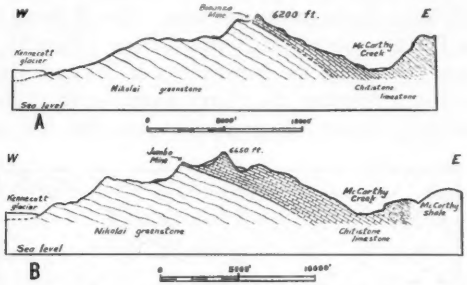


FIG. 3. Vertical cross-section at (*A*) Bonanza Mine and (*B*) Jumbo Mine. No vertical exaggeration.

top of the greenstone was made from all of the available data and it displayed several such unsuspected folds.

Faults and Fractures.—The limestone and underlying greenstones are more fractured and broken than the other formations; the former much more so than the latter, due probably to its more brittle nature. The fracturing may be divided into three classes—faults, sheeted zones, and prominent single fissures without faulting. There is a certain amount of intermingling of all three; faults or fissures may be accompanied by sheeted zones, and faults may be accompanied by sympathetic fissures showing no movement. They fall into four fairly well defined systems, a northeast system, in part mineralized, an E.-W. system slightly mineralized, and unmineralized northwest and N.-S. systems. The faults are mostly northwest and northeast and the sheeting northwest, northeast, and N.-S., while the mineralized fissures are northeast with steep southeast dips.

Nearly all the faults pass from the limestone down into the greenstone, but a striking feature of the district is that the fis-

sures and sheeting mostly terminate at, or slightly above, the greenstone contact. This feature will be discussed in more detail under the heading of Ore Deposits. The concentration of fractures in the limestone has rendered it more susceptible of replacement by copper minerals.

Faults form but a small proportion of the total fractures, and those with large displacements are rare. One of them, the Independence Fault, south of the Bonanza Mine (Plate II., *B*) has a northeast strike, and the northwest side has been dropped at least 300 feet. Another, the Flurry Fault, south of the Jumbo Mine, has its southeast side dropped at least 600 feet and prob-

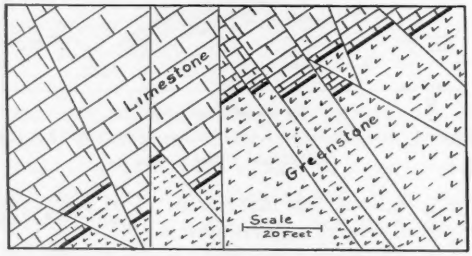


FIG. 4. Faulted contact near Erie Mine.

ably much more. Numerous faults with displacements of from 1 to 25 feet may be seen along the greenstone-limestone contact at the Erie Mine, where the contact is stepped up and down in close succession by normal and reverse faults (Fig. 4).

Numerous faults of small displacement are encountered underground, more being found in the Bonanza than in the Jumbo Mine. They are characteristically discontinuous, horizontally and vertically, and variable in strike and dip. In the Bonanza Mine, faults are equally distributed in the upper and lower levels, but those that show appreciable displacement are more numerous below. The displacements of the veins and of the greenstone-limestone contact has been worked out in about 50 per cent. of the cases. The faults are mostly of small displacement, of dif-

ferent dips, and with variable vertical and horizontal displacement.

Most of the faults are pre-mineral, but many show post-mineral movement, and since partially altered sulphides were deposited in the first, and dragged in the latter, the distinction is often difficult. Conclusions regarding the amount of displacement of ore bodies are usually difficult to obtain and have to be judiciously drawn, for the post-mineral faults may actually be pre-mineral faults with post-mineral movement along them, and the displacement of bedding planes or of the contact may represent the total of both pre- and post-mineral movements.

The region is characterized by so-called "flat faults," which have an important bearing upon the ore deposits. (See Fig. 7.) They are pre-mineral movements along the bedding planes, having the same strike and dip as the beds, but occasionally cutting across the beds at low angles down the dip, and rarely along the strike. They appear to be the sliding of certain beds over others, and are analogous to the movement produced when sheets of paper are moved over each other. Their displacement is almost impossible to determine because of the lack of veins, fissures or other definite fractures crossing them.

Such a strike fault lies between the greenstone and the limestone, and the thin shale band separating them, everywhere shows evidence of considerable movement by its crumpled, gouge-like, slickensided character. An important one in the Jumbo Mine, accompanied by breccia, gouge and slickensides, lies about 40 feet above the greenstone and forms the bottom of the ore (Figs. 6 and 8). A weaker one in the Bonanza Mine lies about 75 feet stratigraphically above the greenstone and in many places forms the bottom of the ore. It also forms, in places, the boundary between the gray and the dolomitized limestone. Several other such flat faults usually marked by an inch or less of black gouge, are scattered through the mines, and in many places have caused termination of the ore.

In our opinion the flat faults may have been caused by a sliding of individual beds or groups of beds over each other, due to the

arching of the major anticline. In such an arching the uppermost beds would be subjected to a stress which would be relieved by breaking, or by sliding upward over the lower beds, in the same way that the outer sheets in a pile of papers arched upward have to slide upward over the lower ones to allow of the arching. If such be the case the flat faults would be reverse.

PHYSIOGRAPHIC DEVELOPMENT.

The physiographic development of the region bears upon the relations of the land surfaces and previous water levels to the origin and superficial alteration of the ores. The record is anything but complete and the presentation of it here is, therefore, rather sketchy.

Pre-Jurassic Development.—As the base of the greenstone in this section is not known, there is no pre-greenstone record. The top of the greenstone is as regular a surface as any sedimentary layer. The even distribution of the amygdules from top to bottom of the individual beds is suggested by Moffit and Capps[10] as one reason for believing them to have been of submarine origin. The relative coarseness of grain of the flows and the entire absence of ropy structure such as occurs in basic subaërial flows also suggests submarine origin. Further, the absolutely unweathered surface of the greenstone as shown in the deeper underground exposures indicates that it was not subject to weathering by the air. It would thus appear that the upper surface of the greenstone was not a land one.

The uninterrupted sedimentation of the Chitistone and McCarthy formations indicates no land area until the completion of the McCarthy shale at the close of the Triassic. Then uplift and tilting of the sea bottom initiated erosional processes which cut down into the McCarthy and Chitistone formations and, in places, into the greenstone. The resulting land surface appears to have been one of maturity with appreciable relief, consisting of relatively flat interstream areas and fairly deep, though gently sloped valleys. The boulders of the basal conglomerate, with a thick-

[10] *Op. cit.*, p. 60.

ness ranging up to 200 feet,[11] in the succeeding Kennecott formation suggests that the land from which they were derived had considerable relief.

Jurassic to Tertiary Volcanics.—The land area next recorded is that developed on the Kennecott formation, and antedating the Tertiary volcanics which form the higher parts of the Wrangell Mountains to the north of the Kennecott area. This surface as seen from Bonanza Peak truncates the older beds and appears to be one of slight relief. It probably extended over the vicinity of the mines, although higher than the present surface. It is not known whether the Tertiary volcanics which lie on this surface ever covered the region in the vicinity of the mines, but they do lie on the Kennecott spur about 9 miles north of Bonanza Mine.

The groundwater level during this period of the development of a surface of slight relief had probably a gently undulating surface corresponding with the topography, a comparatively shallow depth, and with a probable slow downward migration. Its relation to oxidation will be discussed later.

Tertiary Volcanics to Glacial Period.—Deformation of the Tertiary volcanics indicates disturbance subsequent to their extrusion, which, with the erosion that followed, appears to have outlined the main features of the present topography.

A rugged topography seems to have been formed before the start of the glacial period and directed the main lines of glaciation. The master streams flowed in deep valleys and the main tributaries were established. Erosion, apparently, was rapid and great relief was produced. In fact, the main topographic features must have been very similar to those of to-day, except for the accentuation and changes produced by glacial and post-glacial erosion. Moffit and Capps[12] believe that the uplift of the present mountainous areas acted slowly over a long period of time and was later than the Tertiary coal formations of Alaska.

During the carving of the master valleys, and the main tributaries, such as Kennecott Valley and McCarthy Creek, Kennecott

[11] *Op. cit.*, p. 38.

[12] Moffit, F. H., and Capps, S. R., Bull. U. S. Geol. Surv. 448, 1911, p. 74.

Spur, lying between these closely spaced parallel tributaries, was formed, and must have undergone active erosion. The cutting of these two deep, closely spaced, tributaries must have lowered rapidly the groundwater level in the narrow Kennecott Ridge lying between them. (See Fig. 3.)

Glaciation and the Present Surface.—The land carved by stream erosion was profoundly modified by glaciation, which in this country still persists in lessened form. The master valleys and major tributaries were filled by great glaciers, which broadened, straightened, and deepened them; spurs were truncated, lower ridges overridden, hanging valleys formed, and islands of resistant rock left projecting from the floors of the valleys. All those features characteristic of glaciation were impressed upon the country.

Moffit and Capps[13] estimate the amount of glacial deepening to be between 1,000 and 1,500 feet and the top of the Kennecott Glacier to have stood about 3,000 feet higher than it is to-day. This means (and examination of the ground substantiates it) that the ore deposits, lying approximately 4,000 feet above the Kennecott Glacier, were unaffected by widespread ice sheets or large valley glaciers. The upper parts of Kennecott Spur were, however, vigorously attacked by local mountain glaciation, as is attested by the numerous cirques, many of which intersected and produce sharp arretes and steep peaks. Bonanza Peak still supports five short glaciers, one of which is even now sapping the outcrop of the Bonanza ore bodies and enriching its moraine with copper minerals. Elsewhere along the spur, rock glaciers are frequent, and small glaciers are active. The buildings of the Jumbo Mine are built upon the edge of one such small glacier and are constantly moving, while a power line which crosses it show an annual movement in the center.

In addition to the local glacial erosion, frost action played an important part in lowering the general level of the spur and sculpturing the details of the present rugged topography already described. How much of the upper parts of the ore bodies or their overlying cover was thus carried away cannot be told.

[13] *Op. cit.*, p. 44.

Post-glacial stream erosion in the vicinity of Kennecott is almost negligible, because the post-glacial period is yet to come. Here and there shallow notches have been cut by the streams into frozen till or soft rocks. Frost action, however, is active and is now an important agent of erosion. Due to it many of the slopes are mantled by great talus slides resting at the angle of repose and extending in a direction hundreds or even thousands of feet, downward from the base of the steep upper cliffs. The talus slopes are continually creeping downward, due chiefly to the action of snowslides in winters, or of melting snow in spring, and are as continually being renewed.

No evidence of more than one period of glaciation has been observed in the Kennecott district. If an earlier glaciation did take place, its record has been obliterated by the intense erosion of the recent glaciers. It is probable that here as in other parts of Alaska these were periods of glacial advance and retreat[14] and the present period may be one of temporary glacial retreat.

The effect of the glacial period on the ore bodies was to bring about a rapid erosion of their upper parts and to arrest all oxidation or chemical changes within the ore bodies by freezing the waters that would bring about such changes.

ORE DEPOSITS.

General.

The ore bodies at the Bonanza and Jumbo Mines are of the same type, the same character of ore, and exhibit similar behavior. They both occur in the same formations and although a mile apart, were formed by the same processes. In detail and size they differ considerably. Other deposits of the same character of ore and very similar in type, in the immediate district, are the Erie and Mother Lode Mines, both of which have, as yet, made only small ore shipments. The Jumbo and Bonanza have been the great shipping mines.

[14] Such a condition is considered by Capps to have occurred in the White River district. Capps, S. R., *Jour. Geol.*, vol. 23, p. 748, 1911, and U. S. Geol. Surv. Bull. 630, p. 63, 1916.

Character of Ore.

The ore is worked for its copper content, but an appreciable amount of silver adds to its value. No other valuable metals are extracted from the ore or occur in more than microscopic amounts. It is largely sulphide with considerable carbonate of copper scattered promiscuously through it. Occasionally the latter, consisting chiefly of malachite and minor azurite, constitute the chief part of the ore in particular places. Of the copper produced in the last few years, about 25 per cent. has been derived from carbonates. The carbonates have resulted entirely from the oxidation of the sulphide.

The sulphide is almost wholly chalcocite[15] and the great masses and purity of this mineral are one of the striking features of the deposits. The gangue consists entirely of limestone or dolomitic limestone country rock. In places, in and adjacent to the ore, the limestone is recrystallized into white and mottled calcite. Rhombs of pure white calcite are frequent.

Shelter analyses of ore shipments, (1) first quarter of 1915 and (2) last quarter of 1918, show that it contains:

	Copper Per Cent.	Silver Ozs.	SiO_2 Per Cent.	Fe Per Cent.	CaO Per Cent.	MgO Per Cent.	S Per Cent.
1.	69.11	15.96	0.60[16]	0.80	3.42		
2.	63.43[17]	13.73	0.85[16]	0.61	6.16	0.29	13.8

It will thus be seen that the ore bodies were formed by the deposition of copper sulphides, with practically no other minerals or gangue matter. The discussion of this feature will be taken up under "Theoretical Conditions."

Types of Deposits.

General.—In the Kennecott and surrounding districts, copper deposits occur in both limestone and greenstone. Those in the

[15] Other sulphides, in almost negligible quantity, occur. For the amount and description of these see "Mineralogy."

[16] This silica is probably obtained from impurities of the lower limestone country rock.

[17] 11.68 per cent. of this copper is in the form of copper carbonate.

greenstone are most numerous but as yet have resulted in no productive mines. The limestone is the best rock of the only productive bodies and most of them are in the dolomitic phase. The only commercial limestone ores so far known occur at Kennecott, but the greenstone mineralization is widespread, being found over hundreds of square miles. Although this paper is concerned with the ore deposits in limestone it must treat briefly of the mineralization in the greenstone because of its possible bearing on the Kennecott deposits.

Copper in Greenstone.—Copper deposits are found in the greenstone in the immediate vicinity of Kennecott and also scattered over the surrounding districts. All of them show strikingly similar characteristics. The greenstone itself, remote from ore bodies, invariably yields small amounts of copper by assay. J. D. Irving learned in 1907 from examinations of many greenstone localities that hardly a greenstone specimen could be found which did not show appreciable copper, and numerous assays of greenstone from unmineralized areas showed .11 to .60 per cent. copper.[16] The form in which this copper occurs was not determined. The deposits of copper in the greenstone occur as (1) veins. (2) disseminated replacements and impregnation, (3) amygdule fillings.

The veins are the most important and the only type that gives promise of becoming productive. Considerable work has been done on them in the districts surrounding Kennecott. They are mostly short and shallow, terminating abruptly at some cross fracture or bedding plane in the greenstone. Their width is usually measured in inches rather than feet. The minerals are extremely irregularly distributed in the veins. Bunches of ore may be found of such size that their economic possibilities seem realized, only to disappear into a narrow stringer of no commercial value. Most of the veins in greenstone contain chiefly bornite and chalcopyrite with minor amounts of chalcocite. Quartz, calcite and lesser amounts of epidote are the chief gangue minerals. Native copper frequently occurs in the veins, and flat

[16] Statement contained in a private report by J. D. Irving.

slabs of it are often found in joint planes unconnected with veins. Some veins exhibit comb structure with native copper lying between the projecting quartz crystals. Most of the veins appear to have been formed chiefly by a filling of preëxisting cavities, with minor replacement of the walls.

The disseminated replacement deposits are usually narrow and elongated zones of mineralization formed by a partial replacement in and along sheeted zones and are very spotty. They consist of bornite, chalcocite, chalcopyrite, and native copper. The greenstone is usually considerably altered, and chlorite, epidote, albite, calcite, and zeolites occur. A disseminated deposit is reported by Irving[29] on the upper Kotsina River in which native copper averaging 0.65 per cent. occurs in flakes and particles up to ⅛inch in diameter, associated with specks of quartz and minute grains of epidote. The augite of the greenstone has been altered to hornblende indicating deep-seated alteration by heated waters, but the rock has not been altered by surface agencies.

The amygdule fillings are of scientific rather than commercial interest. They occur in widely scattered localities of greenstone, but are not numerous in any one locality. They contain native copper, bornite, chlorites, epidote, serpentine, quartz, calcite, and zeolites. The rock adjoining the amygdules in places contains fresh olivine and iddingsite.

Native copper has been reported from a number of localities throughout the belt of greenstone rocks and is known to occur as placer copper in all of the gulches and streams which cut greenstones. Nuggets weighing up to a pound are common and some have been found weighing several hundred pounds.

Mineralization in Limestone.—The valuable ore deposits at Kennecott occur as fissure veins, irregular massive replacements, and stockworks in limestone. Between the first two classes there are all gradations, the end phases being distinctly veins or massive replacements and the intermediate phases being replacement veins. The third group consists of stockworks, irregular in outline, formed by the filling and adjacent replacement of small

[29] Private Report, 1907.

ramifying fractures and joints. The veinlets are rarely more than a few inches in length, less than an inch in width, and a few inches apart. These constitute the lower grade milling ores. In all of the groups of deposits the amount of ore formed by filling of cavities is relatively small; by far the greater part has been formed by replacement of the country rock. The fissures have acted as channels for directing the circulation of the mineralizing solutions, thereby giving the solutions access to the rock to attack and replace it.

The veins exhibit little evidence of banding, crustification, or other structures characteristic of fissure veins, because their fillings consist chiefly of only the one mineral. In a few places a prominent banding of chalcocite and covellite occurs, and occasional specimens show microscopic banding with other minerals (see page 36). Most of the ore in the veins has been formed by replacement of the limestone walls of individual fractures. The ore may be in the form of one continuous band of solid sulphide or of several bands with braided structure. At one point there may be three or four bands of sulphide separated by narrow bands of limestone; a little further along these may coalesce into two bands or even one, by replacement of the intervening country rock. The individual bands vary greatly in width within short horizontal distances, in places pinching to mere seams, and in others swelling out to a width of many feet. The veins may be accompanied by disseminated sulphides in the walls.

The replacement bodies are of three classes: (1) irregular massive replacement, (2) replacement veins, and (3) disseminated replacement, with all gradations between them. The massive replacements have been localized by fractures or bedding, to be described later, and their shapes are partly controlled by these features. In this class are many examples of replacement so complete that not a vestige of the original rock is to be seen in the ore. In the replacement veins the ore bodies have been localized by zones of fracture in which the fractured rock has been wholly or partially replaced by ore, and the unfractured walls also replaced to varying widths, thus giving the ore body the vein-

like appearance. In the disseminated replacements, grains and veinlets of ore are scattered through massive or fractured limestone. They customarily form a marginal zone to other ore bodies or occupy the area between two adjacent veins or massive bodies. In places, veins of massive ore may pass along their strike into disseminated ores.

In general the replacement was singularly complete where once started, and yet with a few exceptions the solutions which caused the replacement appear to have been passive. They completely replaced the rock with which they came readily in contact, but lacked the vigor to penetrate far into massive limestone away from the fractures, and were terminated abruptly by insignificant slips and bedding planes. It is not uncommon to see a large body of solid chalcocite abruptly ended by a pre-mineral slip containing only one quarter inch of gouge.

The completeness of the replacement and resulting purity of the ore may best be understood by the classes of ore mined. The "first class" or "high grade" consists of practically pure copper minerals obtained from the massive replacements, and massive parts of the replacement veins. Large stopes have been opened in which practically nothing else but pure chalcocite could be seen, so that the stope resembled a black coal mine and the ore as drawn from the chutes has run as high as 70 per cent. to 76 per cent. Cu.[20] Examination of car load lots failed to disclose a speck of limestone. The "second class" ore consists of bunches or bands of copper minerals, mostly chalcocite, either attached to limestone or diluted with it in the process of mining. This class comes from the margins of the massive replacements or from the less massive parts of the veins, and is shipped directly to the smelter. It contains from 20 to 50 per cent. Cu. The milling ore consists of disseminated grains of copper minerals or larger pieces which cannot be mined without much admixed limestone. The individual grains or pieces of copper minerals are themselves practically free from included gangue matter, but are contained in, or attached to, fragments of country rock. This low-grade

[20] Pure chalcocite contains 79.8 per cent. of Cu.

class comes from the margins of other ore bodies, from the disseminated replacements and stockworks, or from those parts of the veins where the mineralization is spotted or where the bands of copper minerals are too small to constitute any considerable proportion of the broken ore.

Talus Deposits or Slide Ore.—A unique deposit of copper ore occurs alongside the Bonanza Mine, mined by nature and gathered on the hillside as a talus slope. The Bonanza vein outcropped as a great mass of rich ore, mostly solid chalcocite, along the top of a knife edge ridge projecting out from Kennecott Spur. (See Fig. 5.) The rapid and continued erosion of the

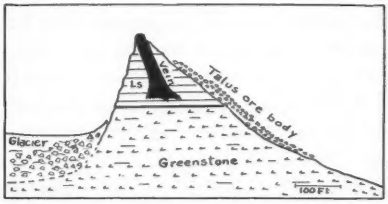


FIG. 5. Diagrammatic cross-section at Bonanza Mine to show glacier ore body and talus slope ore.

ridge and the vein forming its backbone resulted in débris, composed of ore, falling down the side of this steep ridge. Its accumulation on the S.E. side formed the talus slope ore known as the "Slide ore body." It lies at the angle of repose and forms a mass, irregular in outline, extending a few hundred feet up and down the hillside. The thickness is several feet and the width several tens of feet. More than 90,000 tons of high-grade milling ore were thus formed, most of which has now been mined by surface scrapers. The rock fragments vary from small grains up to the size of one's head, and scattered through it are more finely comminuted pieces of copper minerals, chiefly chalcocite free from limestone, with a minor amount of copper carbonate.

Glacier Copper Deposit.—An ice glacier seems an impossible "country rock" for an ore body, yet such is the case on the side

of the same ridge opposite from the Slide ore deposit. Here the ridge falls away almost vertically, forming the side of a steep-walled cirque, which contains a small glacier of no appreciable movement (Fig. 5). The débris resulting from the rapid frost disintegration of the ridge and vein outcrop, accumulated on the glacier for a distance of a few hundred feet from its edge, forming part of the glacial moraine. The débris accumulation and the building up of the glacier went on hand in hand during the Glacial period, for the ore now occurs deep within the glacier. The glacier with a steeply sloping front has been explored by means of three tunnel levels from which several cross cuts have been run, enabling the ore body to be partially outlined and sampled. So far, 220,000 tons of copper ore have been developed.

This ore consists of ice, limestone, and chalcocite, with a minor amount of carbonate; the country rock is ice with considerable admixed rock débris. The ore débris is of the same character as that described for the talus ore, except that larger pieces are more common. Perhaps 30 to 60 per cent. of the material within the ore body is accumulated débris, the remainder being ice. The ore body is quite compact, requiring blasting, and the workings required only moderate timbering. The passage from ore to waste is a gradual one.

Structural Relations.

Relation of Mineralization to Rocks.—In both the Bonanza and Jumbo mines the association of ore and rocks is similar. No ore extends down into the greenstone and none occurs in the lower few feet of the Chitistone limestone. Most of it occurs in the dolomitic phase of the Chitistone limestone, but large bodies are mined in the dark gray limestone beneath the dolomitic phase. (See Fig. 12.)

In the Bonanza Mine the development for some years indicated that the ore was confined to the dolomite, giving rise to the impression that the dolomite was the only favorable host rock, and that all development and exploration should be confined to this rock. The ore did not pass into the so-called "unfavorable"

gray limestone beneath the dolomite, but terminated abruptly at the contact between them.

In the Jumbo Mine the same condition existed to a certain extent, but further development demonstrated that the ore passed uninterruptedly from dolomitic to gray limestone (the latter being as favorable to ore as the former), and that the stratigraphic downward termination of the ore was due to causes to be discussed later.

This conclusion applied to the Bonanza Mine later led to the development of extensive ore bodies in the gray limestone.

In the Bonanza Mine (compare with Fig. 6) the ore bodies are

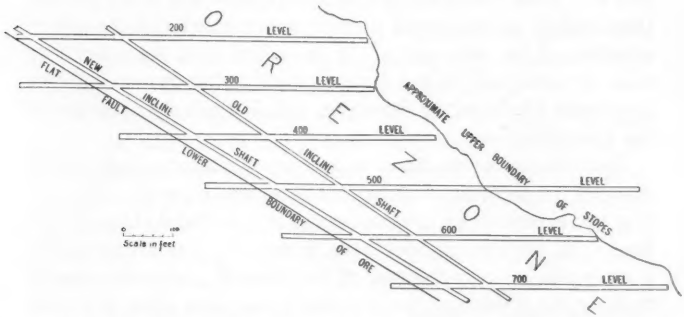


FIG. 6. Longitudinal vertical projection from the 200 to 700 levels of Jumbo Mine to show inclined ore zone and its relation to the Flat fault and rocks. Shafts and main levels, only, are shown. Lateral workings omitted.

distributed throughout an inclined zone whose longer axis pitches downward parallel to the dip of the bedding, and whose shorter axis, normal to the bedding, extends up to a maximum distance of 340 feet above the greenstone or 250 to 270 feet above the limestone-dolomite contact. Within the main ore zone the veins bottom at the gray limestone and Flat fault, but the irregular replacement bodies occur in the gray limestone beneath the dolomite. The upper end of this inclined zone intersects the surface for a short distance; the lower has not yet been exposed by mining.

In the Jumbo Mine the conditions are the same (Fig. 6) except that the inclined ore zone extends to a maximum distance of 500 feet above the greenstone, and the main veins pass downward through the limestone-dolomite contact and terminate abruptly against the Flat fault parallel to the bedding.

The behavior of the main vein where it passes downward from the Chitistone limestone into greenstone can be seen at the Bonanza outcrop. The fissure passes with diminished strength through the lower limestone members, but dies out in the greenstone a few feet from the contact. The ore stops about ten feet above the greenstone, but sparse mineralization extends down into it. Even this ceases within a foot or so and it is so casual that it might be interpreted as being unconnected with the mineralization of the vein above. It is evident that the greenstone does not lend itself to the same fracturing that gave rise to the prominent fissure in the limestone, and is decidedly uncongenial for mineralization.

The behavior of the main vein in the greenstone could not be observed in the Jumbo Mine, for it is not exposed. The ore does not extend to the greenstone and it is doubtful if the fissure does. At the Erie prospect, the fissure dies out in the greenstone within a short distance of the contact; chalcocite extends down to the greenstone, but not into it and gives place to a little chalcopyrite and quartz.

Behavior of Fissures.—The fissures, which have been filled or replaced to form the veins, exhibit unusual behavior. One customarily thinks of fissures as extending from the surface downward (except in the case of blind veins), but the Kennecott fissures extend from the bottom upward and they have also been developed that way. In horizontal direction they resemble any fissure. They are highly inclined and cut across the strata normal to its strike. But in vertical direction they start usually from one of the inclined bedding planes parallel to the greenstone contact and at variable distances above it, and gradually diminish and die out, or pass upward from a clearly defined fissure to a slightly sheared zone of relatively insignificant fracturing. (See

Figs. 5, 7, 8, 12.) Their strongest development is below, and the weakest above. The sympathetic shearing or fracturing which accompanies them also dies out upwards. Their upward extension resembles the roots of the usual type of fissures. The fissures may thus be pictured as tabular bodies whose bottoms are terminated abruptly and pitch downward at 23 degrees parallel with the bedding; whose tops die out in a frayed outline which also pitches downward approximately parallel to the bedding; the whole extending downward along its pitch an undetermined distance. (See Fig. 6.) Obviously the veins formed by the filling of these fissures present the same behavior. The mineral filled fissures exhibit little or no faulting.

Relation of Mineralization to Fractures.—Three factors have been important in localizing the ore; namely, the Chitistone limestone, steeply inclined N.E. fissures, and flat faults.[21].

The limestone, as already described, was the chief localizer of the ore, and also of the fissures and "flat" faults. The fissures governed the position, shape, and size of the ore bodies. They guided the mineralizing solutions through the liemstone, thus localizing the veins and allowing opportunity for massive replacement, and the "flat" faults determined the bottom of individual ore bodies and in places caused local swellings of the veins (Fig. 8). Intersecting fractures in places diverted solutions from the main channels, giving rise to smaller veins, stockworks, or irregular massive replacements.

The fissures, next to the limestone, were the chief loci of ore and thus are a guide in exploration for more ore. The massive irregular replacement bodies in the Bonanza Mine are separated from the main vein, but clearly have been localized by other smaller fissures, although in some cases the fissures are no longer visible within the ore itself.

The flat faults strike almost at right angles with the veins, and their intersection with the veins pitches downward at the angle of the dip of the flat fault. (See Fig. 7.) This intersection acts both as the downward termination of the veins and a favor-

[21] See p. 13.

able locus for ore. The selvage or gouge from a fraction of an inch to a foot or more in thickness, contained in the flat faults, apparently acted as dams to the solutions, for mineralization extends beneath only a few of them. Also the dams of gouge by acting as barriers to the progress of solutions along the fissure, impounded the waters on their upper sides, allowing greater replacement of the walls of the fissures. and caused enlargements of the veins, This is notable in the Jumbo Mine where the main

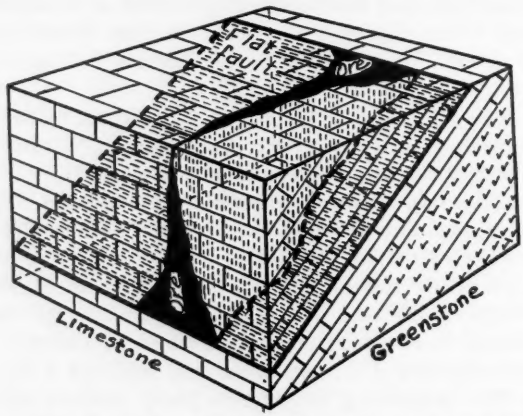


FIG. 7. Stereogram to show flat fault and ore bodies. Note enlargement of ore body at intersection of steep fissures with flat fault, and diminution of ore upward and outward from it.

flat fault with its thick gouge terminated the veins in the upper levels, but in the lowest levels apparently had no influence, because the veins do not come in contact with it. The favorable locus created by the intersection of the two gave rise to the largest individual body of solid chalcocite ever mined, from which thousands of tons of ore were shipped, containing, as mined, over 70 per cent. of copper (Fig. 8).

In the Bonanza Mine a flat fault and not the gray lime beneath the dolomite terminated the ore. It was a coincidence that part way down the incline the flat fault and the contact between lime-

stone and dolomite concurred, giving rise to the erroneous impression that the dolomite was favorable and the gray lime unfavorable for ore. The Bonanza main flat fault, however, is so insignificant as to be almost overlooked. It is an unusually even break, occurs along a smooth bedding plane, and contains only

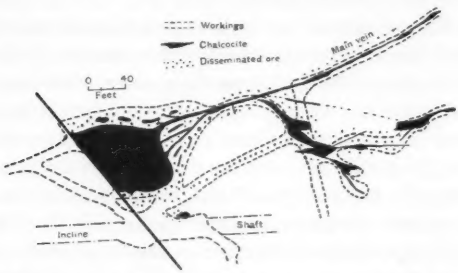


FIG. 8. Plan of part of 500 level, Jumbo Mine showing relation of the "big chalcocite body" to the Flat fault, and the shapes and sizes of ore bodies disclosed on the level.

about one inch of compact gouge. Nevertheless, it appears to have been effective in terminating the downward extension of the main Bonanza vein from the fifth level to the surface. From the fifth level downward other small flat faults appear to have done the same thing. Nearly all of the irregular replacements, the so-called "flat ore," away from the main Bonanza vein, terminate downward against small flat faults, locally named "bedding planes," because they occur along bedding planes, and the evidence of movement is not pronounced. (See Fig. 12.)

Relation to Folds.—At the Bonanza Mine, dips and strikes taken along the greenstone contact indicate a slight synclinal folding or else a monoclinal fold. The fold pitches parallel to the greenstone contact and the trough coincides with the ore zone. Underground exposures of the greenstone demonstrate the same thing. It may be considered simply as a downward warping of the inclined top surface of the greenstone and overlying limestone (Fig. 12). The ore appears to be connected with this fold-

ing and it will be further discussed under the "Origin of Fractures."

Relation of Mineralization to Faults.—The larger faults already described apparently have no relation to the ore but there are in the mines numerous faults mostly of small displacement which have an important relation to it.

Where the pre-mineral faults or fault zones intersect the N.E. mineralized fissures there are local enlargements of the veins; the more brecciated the fault zone the greater is the ore enlargement, and where the intersection is nearly at right angles, the enlargement is greater than where acute. The enlargements are due to the opportunity afforded the solutions to be diverted from the main fissures into the cross faults, bringing about their filling and replacement. Some pre-mineral faults, like the flat faults, have acted as barriers to the further extension of mineralization. Post-mineral faults, or those faults which at least have post-mineral movement along them, have displaced ore bodies.

Shapes and Sizes of Ore Bodies.—In a general way, the veins may be considered as extremely thin wedges gradually tapering upward toward their apex, and their bases resting on an inclined flat fault or bedding plane. The length of the inclined wedges along their base is many times greater than their height from base to apex. The height of most of the veins has been determined, but lengthwise along their base they are still being followed by inclined shafts (Fig. 6). In detail the veins are extremely irregular and depart from the wedge-like shape. The height varies from place to place along the incline; the width along the base varies still more, and also may change greatly from the base toward the apex, perhaps being wider midway up from the base than at the base itself, so that a cross-section at any one point may not show a simple wedge-like shape.

The average height of the main Bonanza vein from the base to the apex, measured normal to the incline, is about 210 feet in the upper levels and 150 on the lower levels. It has been followed for a distance of about 1,900 feet, measured along its base, and the width varies from 2 to 50 feet.

The main Jumbo vein, exclusive of its enlargement at the flat fault, averages about 360 feet in height, from 2 to 60 feet in width, and has been followed down its base for 1,500 feet. The great variation of width in both veins is due to locally greater replacement of the walls at particular places, intersections with fault zones, or junctions with other veins.

The lesser veins in both mines are, in general, similar to the ones described above, but not all bottom on the same flat fault, and their dimensions are not as great as in the main veins. The lesser veins appear to die out along their pitch, as do the main veins toward their apices, and where one dies out other parallel ones have frequently been found to start. Other veins occur in the Bonanza Mine formed by the replacement along vertical or highly inclined fissures which are abruptly terminated above and below by bedding planes. They are simply cracks across thick limestone beds (Fig. 12).

The big Jumbo ore body formed at the intersection of the main vein and the flat fault extends down the incline for a distance of 530 feet and has a maximum height of 100 feet, measured normal to its base. Its base is abruptly truncated against the flat fault and the shape may be seen from part of the plan of the 500 level shown in Fig. 8.

The numerous irregular replacement bodies unconnected with the main vein in the Bonanza Mine are all limited on their bottoms by bedding planes or small flat faults. The tops of many of them are also limited the same way so that they extend as a series of more or less connected bodies up and down the dip of the strata and enclosed within certain beds of limestone. Most of them have a greater width than height, but in a few the dimensions are reversed. Up to the present they have been developed from the surface down to the 600 level. Their shapes are diagrammatically represented in Fig. 9. Other replacement bodies occur in both mines, but notably in the Bonanza Mine, as isolated blebs or bunches of chalcocite up to 15 feet in diameter, apparently unconnected with fissures or other ore bodies.

Relation to Surface.—The moderately pitching ore zone of the

Bonanza Mine has been intersected by the steeply rising surface to form an ore cropping which is a cross-section from bottom to top, almost normal to the base of the zone. Thus the cropping displays the behavior of the veins in vertical extent, affording a cross-section of the wedge, with their bottoms spreading out on a bedding plane and tapering to their apex. (See Fig. 5.)

The relation of the present surface to the ore bodies is purely accidental and their exposure is due to the rapid surface erosion

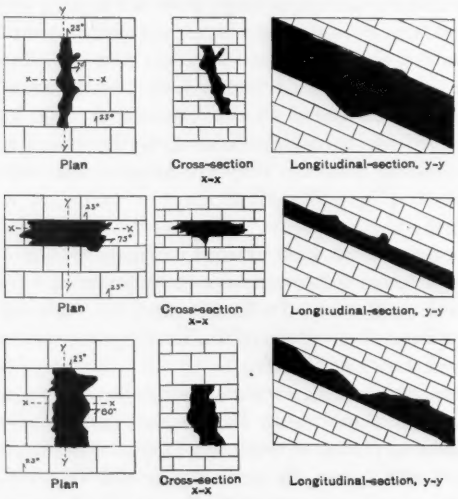


FIG. 9. Diagram to show shapes of three types of irregular replacement bodies and their relation to the bedding planes.

which revealed them. It is a coincidence that, at the Bonanza, erosion had progressed to the point where two parallel veins and the mineralized ground between them formed an ore body much greater in extent than its continuation underground. Had erosion been less deep the great Bonanza cropping might not have been exposed, had it been deeper the big ore body might have been worn away. In the Jumbo the reverse is true; the cropping

although strong gives little hint of the great ore body that lies beneath. The vagaries of erosion were such that it exposed on the surface the weakest part of the vein, but had it extended deeper much of the great ore body might have been dissipated by the processes of mechanical disintegration. The surface croppings, therefore, give but little indication of what might lie beneath, nor does the absence of cropping preclude the possibility of ore below, for "blind" veins have been discovered underground. Hence the advisability of careful study of surface fractures.

Distribution of Ore Bodies.

Each mine contains one main vein and several lesser ones, the number being greater in the Jumbo than in the Bonanza. The lesser veins of the Jumbo are discontinuous vertically and horizontally, so that on different levels the number varies (Fig. 10).

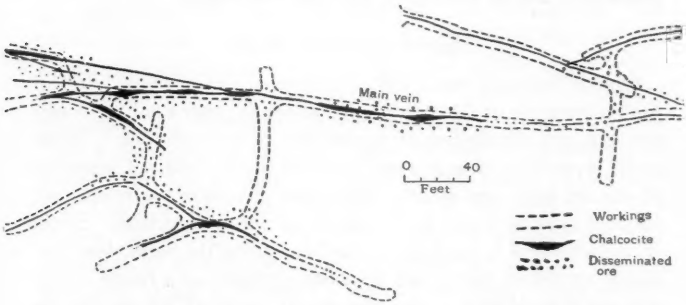


FIG. 10. Plan of part of 200 level, Jumbo Mine, to show shapes and distribution of veins.

Most of them are splits from the main vein that may coalesce with it again or fade out. On the 100 level are 4 separate veins: on the 200 level, 5; on the 300, 3; on the 400, 2; on the 500, 2; on the 600, 4 or 5, while on the 800 and 900 levels as yet only one vein is being worked on each, and these are not the same one. With the exception of the 900 vein all are contained within a narrow zone, and in the upper levels the mineralized walls of the

different ones coalesce to form large connected ore bodies. The excessive enlargement of the main Jumbo vein against the flat fault extends as one continuous ore body from above the 300 level to nearly the 600 level. No detached irregular replacement bodies occur in the Jumbo Mine.

In the Bonanza Mine detached irregular replacement bodies are numerous, being found on all the levels and the number of separate fissure veins is less than in the Jumbo. On the surface and down to the 150 level are two large veins and one small vein; on the 200 and 300 there is only one, and on the other levels two or more occur.

At the Erie and Mother Lode mines similar ores are extracted. Small amounts of mineralization of no present commercial value occur in other parts of the Kennecott area. In more distant areas, mineralization in the Chitistone limestone similar in many respects to that at Kennecott, has been discovered.

Alteration of Host Rocks.

One of the most remarkable features of the mineralization in the limestone is the lack of gangue minerals other than the country rock, and the absence of silicification of the wall rock. Some small crystals of quartz were observed in the oxidized minerals of one ore body, and microscopic grains of quartz occur in a few chips of chalcocite and in the calcite of one thin section. Some of the wall rock is in places crystallized along the veins, forming coarse masses of calcite and dolomite, probably as a result of the mineralizing solutions. But beyond the limits of the ore similar recrystallization occurs, and zones of calcite are common in various parts of the Chitistone formation, as would be expected in a limestone country. The recrystallization evidently preceded the development of the sulphides in some places, for occurrences are frequently observed where the rock carbonates have been attacked along their cleavages by veinlets of chalcocite.

Only a part of the limestone is recrystallized, for occurrences are numerous where not the slightest change can be noted by the naked eye, or microscope, in limestone or dolomite lying against

solid chalcocite. Thin sections have been made of veinlets of chalcocite, including parts of the walls on either side and no change in grain or character could be observed even where a particle of limestone rested in intimate contact with chalcocite.

The dolomitization of the limestone is not related to the ore formation, for it is a widespread feature, whereas the ore is local. Neither was the rock laid down as a dolomite, for the contact between it and the dark gray limestone crosses the bedding. Dolomitization is considered to have preceded the ore formation.

Mineralogy and Mineralography.

Relative Abundance.—The ore minerals, with the exception of the obvious products of oxidation, are listed as follows, in order of their quantitative importance: (1) chalcocite, (2) covellite, (3) enargite, (4) bornite, (5) chalcopyrite, (6) luzonite, (7) tennantite, (8) pyrite, (9) sphalerite, and (10) galena. Of these, chalcocite is by far the most important. In the field, we estimated that it formed 92 to 97 per cent. of the sulphide ore. Covellite probably forms between 2 and 5 per cent. of the ore minerals. The remaining sulphides undoubtedly constitute less than 1 per cent. of the ore. Enargite may be prominent in places and a few stringers have been predominantly of this mineral, but it is absent for the most part in the great chalcocite bodies. Bornite grains over a centimeter in diameter are rare, but specks of microscopic dimensions are fairly common throughout much of the chalcocite. Chalcopyrite occurred megascopically only in a few bunches, which were removed for hand specimens. Luzonite and tennantite are not uncommon under the microscope, but are of no quantitative importance. Pyrite is noticeably absent in most of the deposits; only a few grains were found where the pyritiferous limestone was replaced by ore. Sphalerite and galena are microscopic rarities.

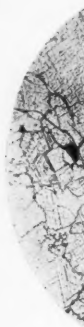
Chalcocite.—Two distinct types of chalcocite occur, *steely chalcocite* and *crystalline chalcocite*. The former is a compact, massive mineral, with no apparent grain, a conchoidal fracture and a metallic steely luster. The crystalline chalcocite has a granular

texture of about the coarseness of a medium-grained marble. The crystalline appearance is largely due to an imperfect octahedral parting which discloses the size and arrangement of the individual grains. The two types commonly grade into each other without sharp boundaries, but in some cases bands of the coarse material occur in the fine and vice versa.

On the freshly polished surface, both types are identical, but when tarnished or etched with nitric acid or potassium cyanide, the difference in grain is revealed. In the crystalline chalcocite a pattern of triangles or rectangles within the grains is revealed by the tarnish which produces lighter bands or strips bounding areas of a deeper blue. Reagents develop similar lattice patterns in the coarser grains and here and there in the smaller (Plate III., *A*). Occasionally, however, in the smaller grains only one set of strong lines is formed similar to the orthorhombic etch-cleavage of chalcocite. In much of the steely material, the reagents and tarnish merely reveal the fine grain without definite patterns within the grains themselves. When etched with nitric acid, the steely chalcocite generally yields irregular patterns resembling cracked porcelain (Plate III., *B*). In much of the crystalline chalcocite, however, the original grain of the material seems lost. The polished surface when slightly tarnished is finely mottled, with here and there a larger bluish area. The mottled material when etched yields patterns like the steely chalcocite, or merely structureless solution surfaces; the blue areas usually yield lattice patterns.

A rarer structure is a peculiar concentric form. Where developed on rather a fine scale, it appears to be made up of an aggregate of small pea-like grains; the field name, *pebbly chalcocite*, is descriptive. Chalcocite with well-developed mammillary surfaces has been observed forming the walls of small open spaces, common throughout the deposit, which gives strong weight to the thesis that the pebbly chalcocite was produced by open-space filling or by the replacement of earlier sulphides formed in this way. On the polished surface the structure of this material is emphasized by concentric cracks in individual grains or by scalloped veinlets of malachite or azurite.

PLATE III



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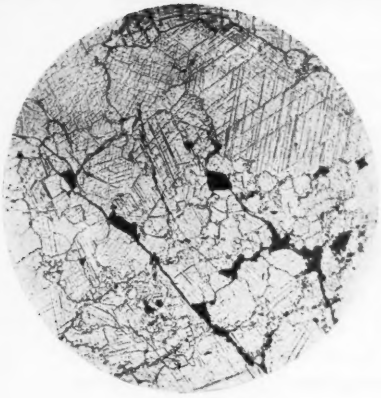
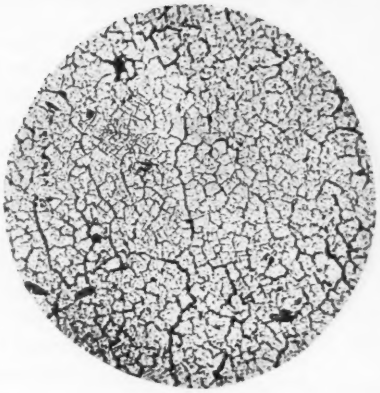
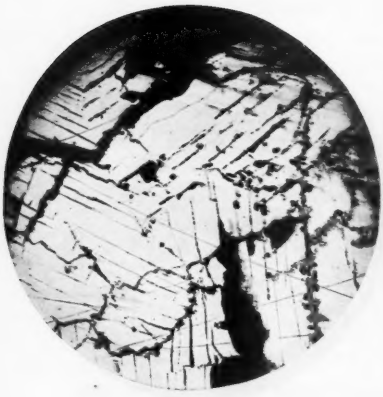


a.



b.



c.

d.

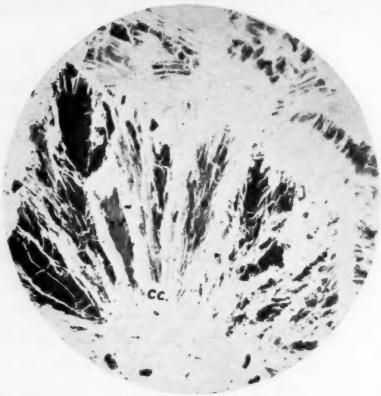
a. Bonanza. "Crystalline" chalcocite etched with potassium cyanide, revealing variations in grain and triangular isometric etch-patterns. × 43.

b. Bonanza. "Steely" chalcocite etched with nitric acid, crackled porcelain structure. × 75

c. Chalcocite from greenstone near Bonanza Mine. Structure revealed by incipient alteration to malachite along orthorhombic cleavage planes. × 43.

d. Bonanza Mine. "Diabasic covellite" (dark) with chalcopyrite (white) and bornite (light gray) between laths. (Variation of tint of covellite due to pleocroism.) × 240.

a.



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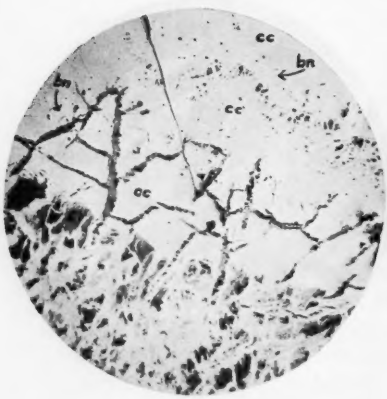


c.

d.

a. Bonanza Mine. Covellite plates (dark) in radial and scalloped patterns partially replaced by chalcocite (white). × 37.

b. Bonanza. Covellite (dark) in radial plates, partially replaced by chalcocite (white). × 70.

c. Bonanza. Covellite (*cv*) partially replaced by chalcocite (*cc*). Veins of malachite in zones of chalcocite. Bornite residues (*bn* slightly lighter than chalcocite) in two bands in chalcocite. × 70.

d. Bonanza Mine. Enargite crystals in limestone. × 40.

The chalcocite is the latest sulphide[21] to form (Plates IV., V.). There is clear evidence that each of the other minerals, with the possible exception of the microscopic rarities, has suffered partial replacement by chalcocite in some parts of the deposit at least. Bornite, as usual elsewhere, is most readily altered, with chalcopyrite a poor second (Plate V.). Enargite and tennantite are less easily replaced, but are not as resistant as the luzonite, which often remains in the chalcocite as fine veinlets or rings, partially corroded, after all neighboring material has been consumed.

Careful chemical studies of chalcocite from the Bonanza and Jumbo mines have been made in the Geophysical Laboratory in Washington. Two analyses and specific gravity determinations have been published,[22] and are as follows:

Sp. Gr. at 25°.	Per Cent. Cu.	Per Cent. S.	Per Cent. Fe.	Per Cent. SiO_2.	Total.
5.610	77.99	21.48	0.26	0.13	99.86
5.606	77.56	21.55	0.55	0.18	99.84

The analyses of chalcocite collected during our work in 1915 are in striking accord with the earlier results. Material from the Jumbo Mine yielded the following values:[23]

	Steely Glance.	Crystalline Glance.
Cu	77.90	77.88
Ag	.07	.09
As	.06	.04
Fe	.17	.17
S	21.33	21.48
Insoluble Gangue	.10	.09
CaO		.11
MgO		.02
CO_2		.11

Covellite.—Covellite of two ages occurs; part is earlier than the chalcocite (Plates III., *D*, IV.) and is clearly unrelated to superficial agencies, and a somewhat greater part is conclusively shown by its intimate association with malachite and limonite to

[21] With the exception of some covellite associated with oxidation products.
[22] E. Posnjak, E. T. Allen, and H. E. Merwin, *loc. cit.*, p. 508.
[23] E. T. Allen, private communication, December, 1915.

be due to oxidizing processes, and to be a first product of the alteration of the chalcocite (Plate V., *A*). This covellite of later origin will be considered on the pages dealing with oxidation.

The earlier covellite occurs here and there in broad crystalline bands through the ore, but it is commonest as aggregates of short laths scattered in the chalcocite. Locally, the blunt crystals may be abundant enough to resemble the distribution of feldspar laths in a diabase (Plate III., *D*), but ordinarily they are very small and form only a subordinate part of the total sulphide. Fine threads of covellite are almost always present, even in the purest chalcocite.

Bands, about an inch wide, of coarsely crystalline covellite penetrate the massive chalcocite in a vein-like manner in several places, but when studied under the microscope, the chalcocite appears to be later, as it forms fine veinlets along the boundaries of the covellite crystals and even breaks across them, (Plate IV., *A*).

In a few specimens, believed when collected to be entirely covellite, the microscope revealed a complex aggregate of blunt covellite laths with chalcopyrite and bornite in the small angular spaces between them (Plate III., *D*), a relation very similar to the feldspar laths and the ferro-magnesian minerals in a medium grained diabase. The covellite laths are sharply bounded and break across the bornite-chalcopyrite contacts without the slightest change, a relationship which suggests uniformity of conditions of deposition of the three minerals and hence approximate contemporaneity. Elsewhere in the deposit, both the bornite and the chalcopyrite are replaced by covellite of the earlier generation; the bornite much more readily than the chalcopyrite.

Bornite.—Bornite occurs in small grains and patches with rather smooth outlines, rarely exceeding an inch in diameter, but most abundantly as tiny specks of microscopic size. It is least abundant or lacking, in the crystalline type of chalcocite, and most abundant in the steely glance. The larger grains are broken in many places by veinlets of chalcocite which afford clear evidence of replacement (Plate V., *B*). Some of the cracks fol-

lowed by the chalcocite veinlets contain malachite or limonite cores, but the oxidized material rarely extends beyond the limit of the bornite grain and only in the case of the larger veins does the crack continue on into the chalcocite field (Plate V., *B*). Malachite veinlets in regular lattice patterns in the chalcocite either do not extend into the bornite or follow curving cracks in it without yielding definite patterns (Plate V., *A, B*). The bornite etches with its usual fine-grained lines but their orientation rarely agrees with the structural directions of the surrounding chalcocite.

Definite lattice patterns between bornite and chalcocite, similar to those described in Bisbee ores, in Butte ores and elsewhere do not occur at Kennecott, but in some places the distribution of faint bluish residues and the patterns of blue and white chalcocite strongly suggest the last stages of replacements of the lattice type. This impression gains support from the occurrence of residual spines or plates of bornite in chalcocite, in symmetrical orientation to its structure, which is strikingly similar to the association common in the bornite-chalcocite ores of the districts mentioned, where the lattice structure is important. Careful study of the contacts usually yields evidence of bornite replacement by chalcocite, and establishes the residual nature of the plates or spines.

The lattice structure is developed also by spines of chalcopyrite in the bornite (Plate V., *D*). The chalcopyrite often shows the same dependence on chalcocite veinlets in the bornite as has been noticed in other deposits, and it is fairly certain here also that the chalcopyrite in this form is a by-product of the reactions by which bornite was altered to chalcocite.

Certain narrow strips of bornite, often with sharp offsets, seem less subject to alteration to chalcopyrite, and usually remain untouched (Plate V., *D*). They greatly resemble veinlets of bornite in chalcopyrite, and in the extreme cases of chalcopyrite formation it is difficult to escape from the interpretation that chalcopyrite was the earlier mineral. However, by tracing the relations from the incipient stages, where a faint band of chalco-

pyrite spines is forming along the margins of these strips of resistant bornite to the final stage, where the main field of bornite has been completely altered and only the strips remain, the sequence of bornite to chalcopyrite may be firmly established.

By these changes intimate mixtures of bornite and chalcopyrite are produced. From them the bornite is altered in many cases to covellite or less commonly to chalcocite (Plate VI., *C*, *D*). Extremely complex patterns result with the covellite in fine lines, specks, or veinlets in chalcopyrite, so intricately and finely spaced that under low magnifications the surface appears almost as if it were a single mineral with a peculiar shade of yellow.

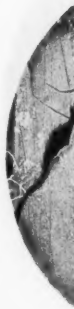
Graphic structures between bornite and chalcocite are rare, and have been observed well developed in only one specimen, but in several cases bornite grains in chalcocite occur in forms similar to the shapes of the blebs of graphic areas.

Bornite continued to form under conditions which produced the earliest covellite, if the reasoning presented on page 38 is to be accepted. This weak continuation or renewal of bornite formation is also shown by certain feeble threads of the mineral, which break later structures, and later minerals as luzonite or, rarely, the covellite.

Nodular Bornite.—A puzzling occurrence of bornite in nodules about the size and shape of pigeons' eggs was noted near the Erie Mine. The nodules are in the lower siliceous limestone, and apparently have no connection with the deposits, either in the limestone or in the underlying greenstone. No structure could be observed in the bornite which would suggest a replacement of a fossil or of any impurity in the rock.

In one nodule studied microscopically the bornite is cut by veinlets, the centers of which are usually malachite and calcite with limonite on the sides. They are bordered by thin margins of covellite which in turn is succeeded inwardly by narrow bands of chalcocite. Many grains of the bornite contain fine lattices of chalcopyrite spines which in places are almost submicroscopic size, and it seems probable that grains with unusual yellowish tints are filled with chalcopyrite of this character, too fine to be detected by our highest magnification.

PLATE V



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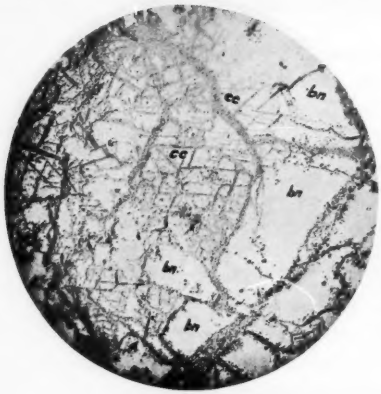
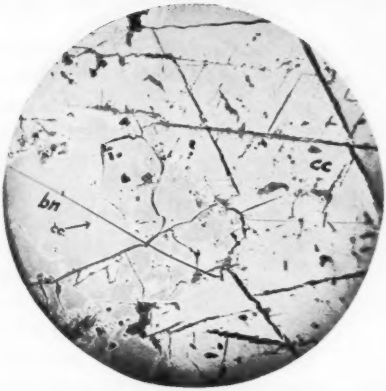
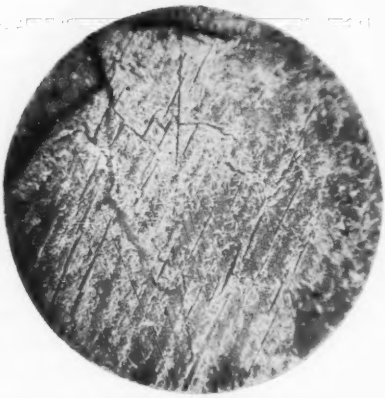


a.



b.

c.



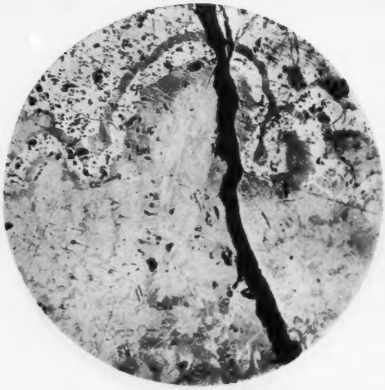
d.

a. Erie. Bornite (*bn*) and chalcocite (*cc*) partially altered to malachite with intermediate covellite in the chalcocite. Veinlets develop triangular isometric patterns in chalcocite, but not in bornite. × 43.

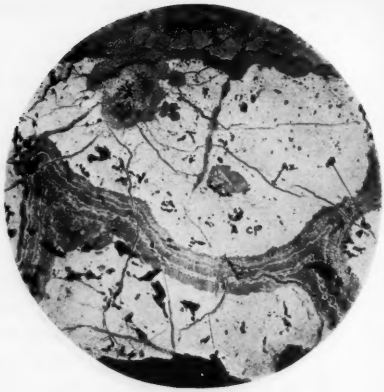
b. Erie. Chalcocite (*cc*) and bornite (*bn*) containing veinlets of chalcocite. Both broken by malachite veinlets (darker gray) which develop triangular isometric patterns in chalcocite, but follow curved irregular courses in bornite. × 70.

c. Jumbo Mine. Chalcopyrite (light) of the earliest generation, partially replaced by bornite (dark). × 70.

d. Jumbo Mine. Chalcopyrite (light) in feathery lattice structures in bornite (dark). Note apparent resistance of bornite in veinlike strips, with characteristic angular offsets. × 240.



a.



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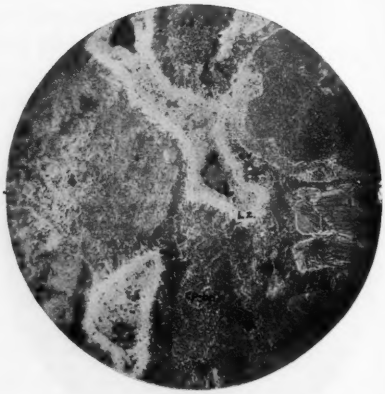

d.

a. Bonanza. Chalcopyrite (light) with bornite (dark), including chalcocite (slightly lighter), in scalloped structures. × 43.

b. Bonanza. Bornite (dark) and chalcopyrite (light) in scalloped structures. Broken by azurite veinlets. × 70.

c. Jumbo Mine. Complex association of bornite (dark), and chalcopyrite (light) and covellite (dark, mottled) in concentric structures. Covellite is largely a replacement of bornite. × 70.

d. Intricate chalcopyrite and bornite (mottled, light gray), with luzonite (?) (white), and coarser covellite (mottled gray) in concentric structures. Crystals now mixtures of bornite, chalcopyrite, and covellite with rims of luzonite. Covellite replaces bornite and forms fringes of radial plates about margins of curved masses of earlier minerals. The luzonite is in part later than covellite. × 43.

The nodule presents a complete record of the alteration of bornite. The slight stains on the surrounding limestone indicate that little except water, oxygen and calcium carbonate have been added to the nodule and that little has been removed. Consequently, the chief work of the oxidizing process has been to rework the mineral combinations with little addition or subtraction of material. As the alteration advances into the nodule along cracks and seams, the copper of the bornite is transposed into chalcocite. Part of the iron liberated by this reaction is forced ahead of the main alteration, and concentrated in the protected interior of the grains, producing the lattice of chalcopyrite; part finds its way into the principal channels, where, with the acidity of the solutions reduced by calcium carbonate from the limestone, it is oxidized and hydrolyzed to limonite, and therefore little iron escapes beyond the limits of the nodule. The continuing attack of oxidation yields covellite from the chalcocite, and malachite as the last product.

The nodule affords a clear picture of the details of the alteration of bornite by superficial agents. It is not a case of enrichment in the casual sense, if the entire nodule is considered, for no copper has been added, but its processes closely resemble those which take place in the enrichment of large ore bodies.

Enargite.—Enargite is not uncommon as coarse crystalline masses, but its usual occurrence is in small amounts throughout the ore, especially in the steely chalcocite. It is usually associated with chalcocite, which partially replaces it, yielding a peculiar brecciated structure, with angular fragments of the enargite set in a cement of blue chalcocite. The replacement of enargite by chalcocite does not seem to be far advanced. The enargite in most cases is clearly a replacement of the wall-rock. Small crystals have been observed in the unaltered limestone with no traces of other ore minerals (Plate IV., *D*). Certain crystals show signs of mechanical changes, being bent and fractured, The fractures are cemented by calcite or by covellite of the early type. The relations to the other sulphides are not definitely shown, but this deformation which was not observed in the others suggests that the enargite was early in the series.

Under the reflecting microscope, the polished surfaces of certain sections of the enargite crystals were found to be distinctly pleochroic. When the longer axis is parallel to the plane of polarization (the plane of the reflecting mirror), the mineral assumes a pinkish tint; at right angles it becomes white or slightly bluish when contrasted with normal enargite white.

Chalcopyrite.—Besides the chalcopyrite previously described, which forms lattice replacements in the bornite, the mineral also occurs in a subordinate way in small grains usually of mutual boundaries toward the bornite (Plate III., *D*), but occasionally corroded by the bornite or broken by its veinlets in ways which convincingly show its earlier origin (Plate V., *C*). Chalcopyrite of the two ages usually may be readily separated in typical cases.

Luzonite.—A pinkish mineral, which has not been positively identified, has been observed in veinlets or small grains in the chalcocite or the less common minerals. It agrees in mineralographic properties with the luzonite in Dr. Murdoch's standard collection. It resembles enargite in general properties, but possesses a deeper pink color in reflected light and is never pleochroic. Qualitative tests on small fragments indicate the presence of arsenic and the absence of antimony and bismuth.

It is rather a late product, for its veins break all other ore minerals except chalcocite. It replaces bornite in the complex chalcopyrite-bornite mixtures, resulting in a lattice of chalcopyrite in a field of luzonite (Plate VI., *D*).

Tennantite.—Tennantite occurs microscopically in certain complex mixtures of bornite, chalcopyrite and covellite. It is in part a replacement of chalcopyrite, for corroded cores of this mineral are frequently found in the tennantite grains. The grains usually possess crystalline outlines. The tennantite is often partially replaced by luzonite which develops in one or two instances a lattice structure identical in appearance with that which occurs between bornite and later minerals. The tennantite is relatively resistant to replacement by covellite and chalcocite.

Pyrite.—Pyrite is widespread as a sparse scattering of small

cubes in the lower siliceous beds of the Chitistone limestone, where it apparently has no connection with the mineralization which produced the copper deposits. Under the flat fault in the Jumbo Mine, a few small grains were found associated with partially oxidized copper ores and much limonite, apparently residues from the replaced pyritiferous limestone.

Sphalerite.—A few grains of sphalerite have been observed microscopically in several specimens, but they yield no information concerning the place of the mineral in the sequence, except that it is earlier than chalcocite.

Galena.—Only a few small specks of galena, doubtfully identified by microchemical tests, were observed.

Concentric and Banded Structures (Plate VI.).—Information concerning the mineral sequence has been gained chiefly from certain peculiar knots in the mass of monotonously uniform chalcocite, in which the rarer minerals of the deposit are concentrated. In the majority of these cases, the various sulphides possess remarkable concentric or banded structures, which on account of their genetic significance are worthy of separate discussion. Chalcopyrite and bornite apparently form the groundmass. They were succeeded by the deposition of tennantite, both as a partial replacement of the earlier sulphides and as crystals apparently forming drusy coatings on the walls of small vugs. Changes in the mineralization processes again produced chalcopyrite, closely followed by covellite in abundance, with a little luzonite and very small amounts of bornite. The chalcopyrite of the second generation forms rims about the tennantite crystals or cuts them in veins. It is most abundant, however, as replacements of bornite in complex aggregates of spines as previously described. The covellite is always abundant. It is prominent in large radial flakes (Plate VI., *D*) in the centers of the concentric areas. From the relations to the crystalline tennantite bands it seems probable that it constitutes the final filling of open spaces. A little bornite in feeble veinlets cutting the later chalcopyrite and the tennantite was apparently formed at about the same time as the covellite. The luzonite is in part contempo-

raneous and in part later than the crystalline covellite. It forms veins in the tennantite and covellite, but also occurs as sharp crystals euhedral toward the covellite fields. In a few instances, fine rims of the luzonite were observed following the serrate outlines of the covellite blades. Chalcocite replaces all the preceding minerals and structures. In some specimens, it is present only as veins or bands parallel to, or breaking across, the complex aggregate; in others, more extreme replacement has left only coarse sheaves of covellite (Plate IV., *A, B*) or rings or bands of resistant luzonite or of tennantite. Some traces of these minerals are usually present in the pebbly chalcocite, or in the mammillary chalcocite, and it is very probable that these peculiar forms were inherited from these complex masses of earlier sulphides.

OXIDATION OF ORE DEPOSITS.

General.

Oxidation in cold northern countries is of scientific and economic importance because of the contrast it offers to oxidation in more temperate climates. Usually ore deposits situated within the northern regions of glaciation have so insignificant a zone of oxidation that the subject is quickly dismissed. The Kennecott deposits are particularly fortunate because, situated as they are, in the midst of an intensely glaciated region and containing a zone of deep and pronounced oxidation, they afford unusual opportunity for this contrast, as well as a study of the relation between oxidation and past climates. They indicate that the presence or absence of oxidation and its attendant economic results in northern regions is not as much one of removal by glaciation or lack of time or temperature conditions since the glacial period, as a study of the *amount* of glacial erosion and time and temperature conditions *preceding* the glacial period. Such a study also involves consideration of the situation, extent, and movement of the ground water in present and past geologic times and in this respect the Kennecott deposits also offer interesting data.

Minerals Due to Oxidation.

The minerals, obviously formed by oxidizing processes are: (1) malachite, (2) limonite, (3) covellite, (4) antlerite, (5) azurite, (6) arsenates of copper, (7) chalcanthite, (8) cuprite, and (9) possibly brochantite. They are listed in the order of their probable abundance.

Malachite.—Malachite is abundant as a replacement of chalcocite, or as a cavity fillings in vugs or other open spaces. It penetrates the chalcocite in veinlets, whose orientation is controlled by the structure of the sulphide, producing lattice patterns, or scalloped bands in material with concentric structure. Less commonly it is also a replacement of limestone; coarse crystals of calcite with malachite (fading into a stain) developed along their cleavages were observed.

Azurite.—Azurite is unusually abundant in proportion to malachite in the Kennecott ores as compared with most regions. Vugs in the chalcocite lined with azurite crystals are common, and in nearly all places where malachite is developed, there is some azurite formed with it. No definite age sequence between the two carbonates could be established however. In some places one is the older, in others the reverse is true. There is a slight tendency for the ratio of azurite to malachite to increase in the heart of massive ore-bodies, and to decrease in the zones of more intense oxidation.

Limonite.—Limonite is small in amount, but is widely distributed throughout the deposits. Stains penetrate the limestone or are diffused through gouge for notable distances. Pure massive limonite is unknown. It is nearly always mixed with malachite or azurite, or with residual limey material or gouge. No limonite gossan occurs.

Covellite.—Covellite is the first product of the oxidation of chalcocite at Kennecott. Its relation to the chalcocite is conclusively shown by the field associations and confirmed by its distribution along the malachite veinlets observed under the microscope. Zones of chalcocite partially altered to covellite exist between unaltered chalcocite on one side and oxidized minerals

on the other. Under the microscope, rosettes and sheaves of covellite commonly accompany malachite veinlets in chalcocite (Plate V., *A*). The spots of covellite, spreading out from the channel-ways, resemble the products of decay advancing into wood (Plate VI., *D*). It is usually closely followed by the carbonates, and there is no doubt that they are successive products of the same general processes.

Antlerite and Chalcanthite.—Antlerite and chalcanthite are associated with secondary covellite in the Jumbo Mine. A large, roughly pipe-shaped mass of oxidized ore occurs parallel to the dip of the bedding at the base of one of the large Jumbo chalcocite body. The chalcocite passes without sharp boundary into a purplish friable material, resembling covellite, but porous and with a low specific gravity. In the intermediate zone between them, chalcanthite occurs in an intermittent band of one half to one inch in thickness. The following results of studies on this purplish material have been kindly supplied by Doctor E. T. Allen and Doctor H. E. Merwin, of the Geophysical Laboratory, through the courtesy of L. C. Graton:

The composition of the covellitic material is:

	Per Cent.
CuS	50.44
$CuSo_4 \cdot 5H_2O$	45.20
Quartz	4.56
	100.20

The 45 per cent. copper sulphate was a surprise as it was not detected under the microscope. Each grain of covellite is very minute and is probably surrounded by a zone of sulphate.[24]

The presence of the quartz was not suspected. None was contained in the overlying chalcocite, consequently it may have been introduced with the oxidizing solutions. The crystals are well formed and each is doubly terminated.

In the field, covellite can be detected cutting the chalcocite in a network of fine veinlets. The material is difficult to polish, but even on imperfect surfaces, the relation to chalcocite was clear. The covellite is without question a replacement of chalcocite.

[24] E. T. Allen, private communication to L. C. Graton, January, 1916.

That the reacting solutions contained copper sulphate is indicated by the presence of the chalcanthite. Chalcanthite, however, is uncommon under normally humid conditions, and its formation here must be attributed to the paucity of water at the beginning of the glacial period.

The zone of covellitic material which is a foot or so in thick-

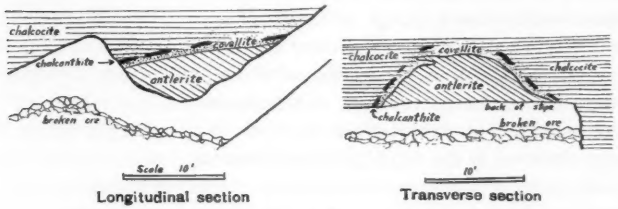

FIG. 11. Anterlite-covellite-chalcocite body, Jumbo Mine.

ness, surrounds an underlying larger mass of light greenish material, which in the field we believed was malachite contaminated with sulphates. The boundary between the covellite and this oxidized product is fairly sharp, but fine stringers of the sulphide extend in lacy masses several feet from the line of contact. Specimens of the purest material which we collected were studied by Doctor E. T. Allen, who wrote concerning the mineral:[25]

> The particular basic sulphate of copper turns out to be $3CuO \cdot SO_2 2H_2O$, and is in all probability identical with antlerite, which is in turn identical with stelznerite. It is very difficultly soluble. I am inclined to connect its formation with the presence of limestone. . . . Of course, basic copper sulphate is formed by the action of water on a dilute copper sulphate solution which contains no free acid.

In later work in the Geophysical Laboratory, it was found that the product of the reaction of a 10 per cent. cupric sulphate solution on marble in the lump at room temperature yielded a product much like the material from the Jumbo Mine.

From this evidence it seems probable that the basic sulphate is the product of solutions carrying copper sulphate reacting with

[25] Private communication to L. C. Graton.

the underlying limestone. The field relations are in accord with this interpretation. The lace work of covellite veinlets may be residues of chalcocite veinlets in original limestone. Very similar conditions have been observed on the edges of unaltered chalcocite ore-bodies.

Cuprite.—One little nest of cuprite octahedra coated with malachite was found in the Bonanza Mine, but the mineral was not observed elsewhere except in small amounts under the microscope. The common occurrence of cuprite associated with native copper, described in connection with the greenstone deposits, offers an interesting contrast, and indicates the control of wall rock on the character of the oxidation. Native copper has not been observed in the deposits in the limestone.

Arsenates of Copper.—Arsenates of copper are formed in small quantities by the oxidation of the enargite-bearing ore. Most of these are mixed with malachite, and have not been identified mineralogically. Mixtures of enargite and chalcocite have been observed to oxidize more readily than the pure enargite. The chalcocite is apparently the more resistant.

Distribution and Depth of Oxidation.

There is no single zone of oxidation, as distinct from a sulphide zone, in the Kennecott mines. Oxidation is just as widely distributed as are the sulphides. Oxidation of sulphides is nowhere complete, yet never absent, except in the interior of massive chalcocite bodies where oxidizing waters have had little opportunity to enter. There is no relation between the amount and distribution of oxidation to the surface, and the lowermost workings show just as much oxidation as the upper, though locally, in both upper and lower levels, certain places may be much more completely oxidized than the adjacent ground. Even blind veins which do not reach within several hundred feet of the surface display pronounced oxidation. The amount of oxidation also seems equally distributed between the base and apex of any individual vein. The oxidation is thus distributed widely. The alteration, however, is feeble; it is rarely thorough, and in most

cases only where an isolated chalcocite stringer happens to be attacked, does it approach completion. Nevertheless, the oxidized copper minerals in the aggregate form 25 per cent. of the ore and led to the building of a special plant for their treatment by an ammonia leaching process.[26]

The actual depth of oxidation may be considered either as the distance from the outcrop down the inclination of the strata, or the vertical distance from the surface to any point. The former is probably the route by which most of the oxidizing waters travelled and the latter is anomalous because the 400 Bonanza level has greater depth vertically below the surface than parts of the 600 or the 700 levels, since the workings extend beyond the ridge whose crest is over the 400 level (Fig. 3).

In the Bonanza Mine, oxidation occurs at a maximum depth of about 1,000 feet vertically below the present surface, on the 600 level, and at 775 feet on the lowest or 700 level. Measured from the outcrop down the incline, the maximum depth is about 1,350 feet.

In the Jumbo Mine the lowest or 900 level shows strongly oxidized ore at a depth of about 1,500 feet vertically below the surface and of about 1,600 feet measured from the outcrop down the incline.

The depth of oxidation beneath the surface that existed at the time the oxidation took place must have been considerably greater than that beneath the present surface for, as will be shown later, the oxidation was pre-glacial, consequently much has been stripped from above the present surface by the vigorous erosion of the Glacial Period.

Relation of Oxidation to Structures.

Fractures.—Areas of intense oxidation are to be found where the sulphides are intersected by faults, fissures, and shear zones. These structural features have acted as channels, which allowed the oxidizing waters to gain ready contact with the ore and to bring about its oxidation. Where the fracturing is post-mineral

[26] A treatment devised and patented by E. T. Stannard, the general manager.

and the ore itself also shattered, the oxidation is more thorough and more spread out. This is especially pronounced in wide shear zones such as the Azure fault. Also the steeper the dip of the fracturing, the more pronounced is the oxidation. In general, the cross breaks which allow unchanged surface solutions to descend to great depths through barren limestone are more important agencies in promoting oxidation than the breaks parallel with the ore. In these, descending solutions are quickly robbed of their powers of oxidation by the easily altered sulphides in the upper parts of the veins. Cross fractures can almost invariably be spotted by the oxidation which accompanies them. The alteration throughout the massive sulphide ore is confined to the surface of joints, small cracks, or to the walls of vugs.

Curiously enough, all the intersecting fractures contain a large amount of limonitic stain. In places the whole drift along such a fracture may be yellowish red in color, while the sulphide itself contains only a fraction of a per cent. of iron. While it is fully appreciated that a small amount of iron may yield an extensive limonitic stain, nevertheless the amount present is striking. This is also found to be the case in workings remote from ore and is even pronounced over wide areas of surface exposures of the Chitistone limestone apparently devoid of known ore.

Bedding Planes.—Bedding planes and flat faults with their bands of gouge have acted as dams, protecting ore beneath them and directing the flow of oxidizing waters down their upper surfaces, thereby causing pronounced oxidation of the lower portions of the ore bodies. This is especially true of the main flat fault in the Jumbo where the upper end of the inclined base of the big chalcocite ore body is completely oxidized to unusual oxidation products. These relations may be seen in Fig. 11.

Relation of Oxidation to Water Level and Climate.

Present Climate.—During ten months of the year, and often longer, the ground at the mines is frozen and snow lies upon it. Frost may occur almost any night in the summer months and the

surface seepage water is always icy cold. In fact, water is difficult to obtain and the amount necessary for operation at the Bonanza Mine is largely obtained from melted snow. These conditions are most unfavorable for present surface oxidation. Broad faces of chalcocite, broken by mechanical disintegration, have not developed more than a thin tarnish from their exposure to the air and wet, and pyrite cubes in the lower limestone show almost no alteration where exposed. The persistence of fragments of sulphides in the loose material of the slide ore body, often as bright as that freshly broken underground, exposed as favorably as possible to the influence of oxidation, attests forcibly to the negligible extent of superficial chemical decomposition under present climatic conditions.

Underground Temperature.—Underground, the conditions are even less favorable for oxidation than on the surface. Temperature readings taken in the middle of summer at different places on different levels showed an average of 30.4° F. in the upper levels, with a range from 30° to 32° F. Only at the portals of the tunnels did the thermometer rise above 32° F., and in one confined drift where a number of men were working. In the two lowest levels of each mine the range is from 31° to 32° F., the latter figure being uncommon. 31.5° F. might be taken as the average figure on the 700 Bonanza and the 900 Jumbo levels. The mines are dry and dusty and standing water freezes. Ice is a common mineral, occurring as splendid crystals lining the walls of drifts near the surface, and as a fissure filling. Slickensided ice was also seen. There is no circulation of water at present, consequently no appreciable oxidation is possible.

Water Level—Past and Present.—From the fact that the Kennecott spur owes its elevation to the rapid pre-glacial cutting of the McCarthy Creek Valley on the one side and the Kennecott Glacier Valley on the other side (Fig. 3), and that these valleys must have constituted the local hydrostatic base level, it follows that the lowering of the groundwater in the ridge must have been faster than erosion on the ridge itself. Under conditions of groundwater progressing downward more rapidly than erosion,

incomplete oxidation usually takes place and this feature may explain the lack of complete oxidation in the Kennecott deposits. Such a condition of deep cutting on either side of a narrow ridge would tend to produce a deep water level within the ridge. It would also cause considerable motion of the groundwater downward to the nearby deep valleys and the flow would be more rapid along channels of easy movement, such as fractures, than in the inter-fracture areas. Such conditions of deep and relatively rapidly downward moving groundwater would also give rise to an irregular surface of the water table; lower where prominent fractures occur and higher in the inter-fracture areas. These features are exactly the conditions required to explain the circumstances, already described, of intense oxidation produced along fractures, the paucity of it in inter-fracture areas, and the great depth to which it has gone.

Under such conditions of topography, the water level can hardly be considered to have been the customary sea of slow moving or stagnant water, for the great head would propel it toward the adjacent deep valleys and the numerous fractures would facilitate and accelerate the downward movement toward a lower outlet. It might be likened to a bath-tub full of water, with water pouring in and also running out by drain pipes, so that there is a continuous, rapid, downward motion. Under such circumstances, oxygenated waters could travel downward in conduits far below the surface of the groundwater and produce deep oxidation.

Before the oxygenated waters had completed their work of oxidizing the sulphides they were arrested by the frigid climate of the Glacial period, and frozen to form a "fossil groundwater" which has remained to the present. The mine workings disclose that all fractures, vugs, cavities, and pores are partly or completely filled by ice. It was the last mineral to form and encloses oxidation products. But the two lowest levels of the Jumbo Mine and the lowest one of the Bonanza are completely free from ice or water and the second lowest level of the Bonanza is almost free from it. They are dry and dusty with open frac-

tures and vugs and show considerable oxidation. The mine workings have thus penetrated a zone of frozen water, which in pre-glacial times was liquid. The bottom of the zone is wavy and exhibits prominent peaks and sags. Where the rock is not greatly fractured the ice zone extends lower and forms sags, but in prominent fractures like the Azure fault the peaks run well up into the frozen zone.

The interesting question arises as to whether this was originally the bottom of the groundwater, such as has been found in many deep mines. The abundant oxidation on the bottom levels, and the shape of the cross-sections of the ridge rather precludes this, however. If the mine temperatures were to be raised now, these openings would unquestionably become filled by water. The condition may be conceived as being due to frost encroaching downward and freezing the waters, but before the waters occupying openings in the lower levels could become frozen and fixed, they drained downward and left open cavities which could not again be filled by the overlying frozen waters.

Age of Oxidation.

The foregoing paragraphs indicate that present oxidation on the surface is negligible, while none can take place underground. It antedates, therefore, the freezing of the waters underground. This freezing must have taken place shortly after the inauguration of the low temperatures of the glacial period, so that all of the oxidation must have occurred in pre-glacial time. This conclusion is further supported by the fragments of oxidized ore sealed within the ice of the Glacier ore body. They must have fallen in during the building up of the glacier in the Glacial period and since they cannot have become oxidized since then, they must have been oxidized before that time. Their presence in the glacier also indicates that the ore body outcropped in the Glacial period and was not first exposed by the erosion of the Glacial period. All of the oxidation is, therefore, pre-glacial.

Oxidation of the ore deposits probably started during the development of the mature surface upon which the volcanics were

extruded. (See p. 15.) The water level was probably shallow at that time and migrated downward very slowly, giving those conditions under which thorough oxidation usually takes place. The greater part of the oxidation at present exposed, however, most probably took place during the time of the rapid erosion immediately preceding the Glacial period. Then, the topography and erosion were such as to give rise to the incomplete and deep oxidation so characteristic of the Kennecott deposits. The process of oxidation was vigorously operating until it was arrested by the Glacial period.

THEORETICAL CONSIDERATIONS.

Origin of Fissures.

Suggested Hypothesis.—The origin of the fissures of such unusual behavior has been a puzzle since they were first studied; various hypotheses were tested and discarded in the successive seasons. The usual theories of origin of fissures do not apply, because wedge-like fissures of little or no faulting, starting from the bottom and dying out upward, are decidedly different from ordinary fissures.

One hypothesis conceived in the spring of 1917 and tested in the field the following season appears to be borne out by the field relations, namely: that the fissures were formed by the stretching of the limestone beds due to a slight synclinal folding, or possibly a monoclinal fold, superimposed upon the flank of the major anticline, with its axis parallel to the dip of the limestone strata and normal to their strike. Careful mapping by structure contours underground and on the surface at the Bonanza Mine demonstrated that such a syncline or possibly a monocline exists, and that the ore bodies are located in its trough. The lack of sufficient exposures at the Jumbo prevented a similar test being made there. Such a synclinal fold would cause a stretching of the lower beds or the lower part of any group of beds, and a compression of the upper beds or the upper part of any group of beds. In brittle rocks such as limestone, under light load, the tension would be relieved by fissuring at or near the place where

the tensile stress was greatest. The fissures thus formed would trend along the line of greatest stress, or along the trough of the syncline or monocline; they would start at the bottom of some strata and extend upward to a point where the tensile stress diminished sufficiently that it no longer needed relief by rupture; the fissures would be strongest and most numerous at the bottom and taper upwards to the point where they died out; they would also probably start from the bottoms of more than one bed. Beds, or groups of beds acting as a unit, would, if of considerable thickness, contain fissures of considerable dimensions; if of small thickness, fissures of small dimensions. Fissures formed in this manner would start (and thus be abruptly terminated downward) at any prominent parting in the beds, such as strongly developed bedding planes or flat faults. More or less parallel fissures would be formed, staggered with each other, longitudi-

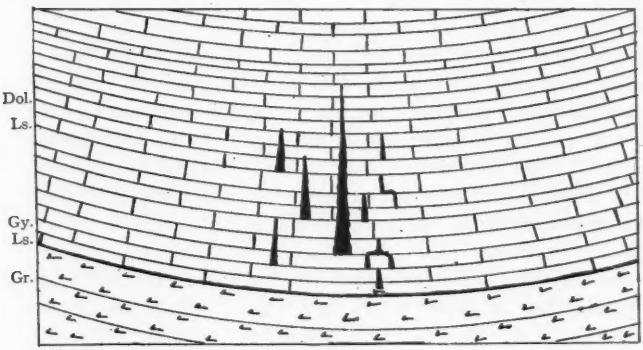

FIG. 12. Diagrammatic vertical section to illustrate probable method of formation of wedge-shaped fissures (black) near axis of slight synclinal fold. Beds dip away from reader. Bottom of fissures follow same dip as beds; the tops approximately so. Greatest dimensions of fissures is along dip.

nally and vertically. The above conceptions are diagrammatically shown in Fig. 12, which is also a diagrammatic cross-section of the ore zone.

This hypothesis would adequately account for the inverted, wedge-like shape of the veins; their downward termination at the flat faults, and the shorter fissures extending across a few beds only. The upward termination throughout their length, at an approximately uniform distance above the base, is readily explained by the cessation of the rupturing due to lessened tension at a definite height from the bottom. The distribution of the mineralized fissures and the lack of appreciable faulting along them is in keeping with the theory, and their confinement to the brittle limestone is to be expected. In short, the suggested hypothesis appears to explain readily all the features of the fissures previously discussed.

A comparison with some of the structural features of the Mississippi Valley lead and zinc deposits is enlightening. Discussing the origin of the fractures in the Wisconsin area, Chamberlain states,[27] "where the beds were (originally) bent downward, as in the case of the ore-bearing basins, the horizontal force would cause them to bend more deeply, and these would likewise be most fractured along the bed of the depression. In each case the fractures would gape mainly on the outer curve of the strata, *i.e.*, on the under side of the sag." Again Chamberlain states,[28] "that they were formed as here indicated by the necessary fracturing of the bent strata on the outer side, is, I think, placed essentially beyond question by a consideration of the significant circumstances, (1) that they lie in stratigraphic depressions, (2) that both their upper and lower flats habitually sag, (3) that they lie almost wholly in the basal beds of the stratum bent . . ." On the following page he concludes. "that the strata should furnish a suitable receptacle for the ore at a given horizon and not above or below, is clearly indicative of some general physical cause." The most notable difference in the structural relations of the two is that in the Wisconsin area the synclinal depressions are in the form of basins, whereas at Kennecott it is a long trough. This difference would account for

[27] Chamberlain, T. C., "Geology of Wisconsin," vol. IV., 1879, p. 484.
[28] *Op. cit.*, p. 486.

the more elongated fissure-like character of the Kennecott fractures.

Another process may have operated, along with the slight folding, to help produce the fissures, namely, in the slipping of the individual beds of limestone over each other and particularly of the lower part of the Chitistone formation over the greenstone, along the shale contact, bumps or other irregularities on the planes of sliding would cause one part of the overlying beds to be differentially elevated or depressed with respect to the other, thereby producing stresses which would result in rupture. Differential movement alone, greater nearer the greenstone and less removed above it, similar to that which operated in the San Francisco earthquake fault, could also produce such rupturing without the necessity of irregularities.

The connection between mineralized fissures, many of which do not outcrop, and synclines or other irregularities, could, if positively established, be used as a criterion for indicating other localities favorable for exploration for more ore, by accurately locating from surface exposures all down warps.

Origin of Mineralization.

Under this heading will be considered the immediate source of the metals originally deposited in the limestone, as well as their ultimate source. The understanding of the deposits will not be complete unless the agencies of transportation by which the metals were brought to the limestone, and their routes of travel, are also discussed, and finally, the means by which the metals were transferred from their carriers to their resting place as the minerals of the ore deposits.

Source of Metals in the Limestone.—In a mineralized region where igneous intrusions occur, the natural tendency is to attribute the ore to the igneous rock, not from habit, but because it usually proves to be the case. Indeed, almost all of the large copper output of the United States comes from deposits which are clearly related to igneous intrusions. In the Kennecott district, however, there is no apparent relation between the ores and the

porphyry. The porphyry shows no traces of mineralization, either in the heart of the Porphyry Mountain stock, or near its edges, or in its apophyses. The three-foot dike of porphyry at the Erie prospect which cuts the ore, is absolutely unmineralized, and the large dike in the limestone above the Jumbo, situated in the rock most susceptible to mineralization, shows no traces of mineralization. There is no evidence indicating that the mineralization was derived from the porphyry. On the contrary, the absolute lack of silicification of the wall rocks, the absence of silica and iron in the ores, and the mildness and monotony of the mineralization, make it difficult for us to believe that emanations, even from a remote magma, produced ore deposits of the Kennecott type. The Erie dike which cuts the vein, indicates mineralization antedating the intrusive, though it does not definitely prove that the mineralization was earlier than the main porphyry stock, for the stock and its apophyse may have been separated by quite an interval of time.

On the other hand, the presence in the ore of a mineral like enargite suggests that the porphyry magma might have been the source of the metals. This, considered with the occurrence of some copper at Bisbee, Arizona, in unaltered limestone remote from the porphyry, but believed to be genetically connected with it, indicates that the porphyry at Kennecott cannot be entirely eliminated as the source of the metals.

The barren limestone may be dismissed as a source, and the remoteness of the Tertiary volcanics, and the lack of any known mineralization associated with them, makes it extremely improbable that the copper was derived from their activity.

The greenstone is copper-bearing wherever exposed and the association of copper with it is just as constant over the hundreds of square miles of its exposure as is the well-known association of iron with the Clinton formation. Hundreds of samples have demonstrated an appreciable copper contact. The widespread disseminated copper in the greenstone could hardly have been formed simultaneously with the copper concentrations in the limestone, for its wide distribution precludes this. But the copper

concentrated in the greenstone in the form of veins and stringers may have been part of the same concentration that produced the deposits in the limestone, for veinlets break across the greenstone limestone contact at the Erie. The widespread copper, however, is not concentrated in veins, but exists in an indistinguishable unknown form. Thus, the greenstone seems the most plausible source of supply. Moffit and Capps[29] also believed that the deposits were derived from the widely disseminated copper in the greenstone.

The derivation of the copper from the greenstone does not necessarily imply that it came from the immediately adjacent greenstone; in all probability it was chiefly derived from more distant parts, both vertically and laterally.

Source of Copper in Greenstone.—A distinction must be made between the copper widely distributed in the greenstone and that concentrated into veins or stringers; the former is a phenomena as widespread as the greenstone itself, and is essentially a feature of the greenstone formation, the latter is localized and is a result of some localizing agencies which operated within the greenstone. It is believed that the veins and stringers in the greenstone may have been formed at the same time and by the same processes that operated to produce the concentration of copper in the limestone. Certainly, at the Erie, veinlets of copper minerals pass from the greenstone into limestone.

The occurrence of the small quantities of widely distributed copper in the greenstone is similar to that described in numerous localities where copper occurs in basic lavas.[30] The forms assumed and the metallic and gangue minerals are all characteristic of this world-wide type of mineralization.

[29] U. S. Geol. Surv. Bull. 448, 1911, p. 81.

[30] Lake Superior region; White River District, Alaska; Coronation Gulf, Canadian Arctic; Eastern Oregon; Triassic Traps of New Jersey and Connecticut; near Lurray Val; South Mt., Pa.; the Bay of Fundy, Nova Scotia; the Faeroer, north of Scotland; Sterling in Scotland; Oberstein a. d. Nabe, Germany; Sao Paulo, Brazil; the Kristiania Region, Norway; New Guinea; the Transbaikalian provinces on the Dochida River; Monte Catini, near Livorno, Italy. (For general discussion and references to literature of the above districts see Lindgren's "Mineral Deposits," p. 392.)

The distribution of the copper through all parts of the Copper River greenstones, supported by the common association of copper with basic extrusives elsewhere, points to the lavas themselves as the original source of the metal. Lindgren writes:[31]

> Basic igneous rocks such as gabbro, diabase, basalt, some andesites and basaltic flows designated melaphrye or amygdaloids probably contain copper, in some cases as much as 0.1 or 0.2 per cent., but commonly about 0.02 of the metal.

According to Volney Lewis and F. F. Grout, the copper is present as a silicate, possibly in part as a sulphide such as bornite or chalcocite. Instances from the literature might be multiplied to show the prevailing opinion that the basic rocks contain copper.

Considerable difference of opinion exists concerning the mechanism by which the concentration of copper in the lavas was affected. As the copper is intimately bound up with zeolites and the latter are relatively diagnostic minerals, their elucidation may explain the occurrences of copper. Commonly they are considered as being formed by descending waters near the surface, and are so regarded by Whitney, Pumpelly and Wadsworth for the Lake Superior region. Van Hise[32] regards them as products of descending surface waters, or similar percolating waters in the zone of cementation, although he later attributes them to ascending waters. Weed[33] believes those in Virginia and Pennsylvania to have been formed by surface infiltrations. Lane[34] believes the Lake Superior lavas to have been submarine, and attributes the concentration of copper to the action of heated sea water on the beds. Fenner[35] regards them as the result of lava flows encountering water in shallow lakes or playas. Lewis[36] assumes hot solutions of cuprous sulphate released from the magma to account for the copper in New Jersey traps, while Knopf[37] at-

[31] *Op. cit.*, p. 393.

[32] Van Hise, C. R., U. S. Geol. Surv. Mon. 47, 1914, p. 333.

[33] Weed, W. H., "Types of Copper Deposits in the Southern United States," *T. A. I. M. E.*, vol. 30, 1900, p. 449.

[34] Lane, A. C., *Proceedings Lake Superior Min. Inst.*, vol. 12, 1906.

[35] Fenner, C. N., *Annals N. Y. Acad. Sci.*, vol. 20, Pt. II., 1910, p. 97.

[36] Lewis, J. V., Geol. Surv. N. J., 1906, p. 131.

[37] Knopf, Adolph, Econ. Geol., vol. 5, 1910, p. 247.

tributes the disseminated copper in the lavas at White River, Alaska, to hot solutions circulating through the lavas soon after their extrusion. As proof of the latter point, he describes a copper-bearing amygdaloid covered by a coarse pyroclastic bed, the breccia of which contains fragments of the cupriferous amygdaloid, proving that the mineralization took place during the interval between successive flows. Lindgren[38] points out that zeolites are unstable in the zone of weathering and must have been formed at some depth, and states:

> Following Lane (p. 406), I believe that the water of seas or lakes, mingling with the exhalations from the magma, decomposed the copper silicate in the pyroxenes, and that the resulting chlorides of iron and copper were decomposed by silicates or carbonates of calcium, with the formation of native copper, ferric oxide and calcium chloride.

The development of albite, epidote, chlorite, iddingsite and datolite in the Nikolai greenstone indicates they are not the product of cold meteoric waters, but rather of heated waters, probably volcanic after effects, and such waters must have been as widely distributed as the greenstone. They cannot, therefore, have been a result of a few local porphyry intrusions. The submarine extrusions may also have played an important part in the formation of the copper in the manner indicated by Lane and Lindgren, for, as previously pointed out, the evidence is strongly suggestive that these flows were extended beneath water.

Agents of Transportation.—Aqueous solutions are the only agency that could have searched the copper out of the greenstone and transported it to its present abode in the limestone. That the solutions were not cold, is suggested by the enargite in the ore, a mineral which in Butte occurs most abundantly in the zone where the highest temperatures are supposed to have prevailed. Lindgren,[39] however, says enargite "rather favors the deposits formed relatively near the surface," and Clarke[40] implies that it is a low temperature mineral. But no instance is known to the writers

[38] *Op. cit.*, pp. 397 and 399.

[39] *Op. cit.*, p. 597.

[40] Clarke, F. W., "Data of Geochemistry," U. S. Geol. Surv. Bull. 616, 1916, 661–

where it is considered to have been formed from cold solutions.

The strongest proof of the temperature of the solutions is to be deduced from the chalcocite. Investigations of sulphides of copper at the Geophysical Laboratory[41] have shown that chalcocite is dimorphous; an isometric form is produced above 91° C. which passes into an orthorhombic form below that temperature. At temperatures below 91° C. only the orthorhombic chalcocite is produced, and it is, therefore, the stable form under conditions pertaining at the earth's surface. They also found that chalcocite may contain covellite in solid solution and when the amount of dissolved covellite exceeds 8 per cent., there is no inversion. Thus chalcocite containing over 8 per cent. covellite, formed above 91° C., remains in the isometric form at normal temperatures. Among the copper sulphides investigated by them was some Bonanza chalcocite, in regard to which they state:

> It is further significant that analyzed samples of the Bonanza ore show about 9 per cent. of dissolved cupric sulphide (covellite), a quantity sufficient to prevent isometric crystals which may have formed above 91 per cent. from going over into the orthorhombic form as cooling progressed.

They also state:

> If solid solutions containing even 15 per cent. of covellite could be crystallized at temperatures just below 91 per cent. they would probably etch like ordinary (orthorhombic) chalcocite.

Etched surfaces of the Bonanza chalcocite show isometric patterns (Plates III., V.) which resembles those yielded by etching the artificial isometric chalcocite produced at the Geophysical Laboratory, thus suggesting that the Bonanza chalcocite was formed above a temperature of 91° C. The isometric patterns were first described by Graton and Murdoch,[42] who believed them to be inherited from bornite (isometric). Tolman[43] also described some Bonanza chalcocite and concluded that its isometric etch pattern was inherited from replacement of bornite. These

[41] E. Posnjak, E. T. Allen, and H. E. Merwin, "The Sulphides of Copper," ECON. GEOL., vol. 10, p. 491, 1915.

[42] *Trans. Amer. Inst. Min. Engrs.*, vol. 45, p. 1914.

[43] *Trans. Amer. Inst. Min. Engrs.*, vol. 54, p. 402, 1916.

conclusions thus throw doubts upon the original isometric form of the chalcocite and consequently upon its temperature of formation having been over 91° C. A specimen collected by the first-named writer in the summer of 1918 showed an isometric pattern in the hand specimen, and one piece measured by the goniometer proved to be octahedral. These measurements were later confirmed by Dr. Merwin, of the Geophysical Laboratory. Whether the octahedral angles are to be interpreted as cleavage or parting could not be conclusively determined. In examining material from a 1915 collection, Dr. Merwin found a number of twinned crystals in the chalcocite, which he believes from measurements of the angles to be octahedral twins of chalcocite. It is the first recognition of isometric chalcocite crystals in nature.[44] The evidence of isometric chalcocite presents a strong case for the thesis that the solutions which formed the Kennecott ores had a temperature of at least 91° C. (See also pages 73–77.)

The character of the alteration of the greenstone also indicates that it was formed by thermal solutions. This alteration may have been brought about by the agencies that produced the original widespread dissemination of copper, or by the solutions which gathered up the copper from the greenstone and concentrated it in large bodies in the limestone and as small veins in the greenstone. The latter seems more probable, and if true, the solutions that carried the copper into the limestone were hot.

The above evidence, though not conclusive, is strongly indicative that the solutions were heated, and since magmatic waters given off from the porphyry intrusives do not seem probable (see page 58), some other source must be sought for the warm solutions.

The thesis is presented that the mineralizing solutions were probably meteoric waters with their activity increased by addition of heat and solutes. The waters in travelling through the rocks would have acquired carbonates, sulphates, chlorides, carbon dioxide, and probably some hydrogen sulphide and would, therefore, be competent solvents for the copper in the greenstone. In-

[44] E. T. Allen, private communication.

creased temperature would accelerate their dissolving power. It is possible that the heat retained in the greenstone lavas may have raised their temperature, although this is not probable, because such heat would likely have been lost during the long interval of the deposition of the limestone. However, the temperature gradient in this region must have been high at about the time the ores were formed. Preceding the ore-deposition was great volcanic activity, which gave rise to the Nikolai greenstone; at about the same time as the mineralization, or slightly later, the porphyry intrusions took place, and in the early Tertiary were extensive volcanic eruptions, which are still evident in Mt. Wrangel, a short distance away. A magmatic reservoir must have extended beneath this region which, from time to time, emitted magma, part of which was poured out as a molten fluid on the surface, and part was arrested before reaching the surface, giving its heat to the surrounding rocks.

Heat emanations must have preceded the upward movement of the porphyry magma and the intrusions, which were not deep-seated ones, may have been sufficiently close to the time of ore formation to supply sufficient heat to raise the temperature of meteoric waters, even if they did not come in direct contact with the magma. Such solutions would not contain the large amounts of silica, iron, and smaller quantities of other metals, so typical of waters which emanate directly from magmas.

The heated waters searched the copper out of the greenstone and in their circulation took advantage of established channel ways where copper would be deposited if conditions were favorable. Favorable conditions did exist in the small fractures in the greenstone and in the larger ones in the limestone, giving rise to veinlets in greenstone and large bodies in limestone.

Under such an hypothesis it might well be argued that deposits should occur in many places throughout the greenstone and limestone areas. Perhaps they do, but none of great commercial importance other than those mentioned have yet been discovered. Several deposits have been found in the Chitistone limestone, and the country is dotted with prospects in the greenstone, some of

which have excited high hopes, and a few may yet be small producers. The greenstone, under most favorable conditions of solutions and supply of copper, is uncongenial for ore, and the formation of deposits that do occur in it took place in spite of this difficulty. It is a noteworthy fact that the best of the deposits in greenstone are usually located near intrusives similar to those at Kennecott, which were capable of heating the waters. The wide distribution of small deposits in the greenstone may well be due to the fact that the solutions were present, the copper was available, but the temperature conditions were not proper for concentration into larger bodies. Where larger bodies do occur in the greenstone, temperature conditions were suitable, but the rock was too uncongenial to permit of the formation of extensive bodies, such as might have occurred had the country rock been limestone instead of greenstone.

Method of Deposition.—Most of the deposition of the copper minerals in the limestone took place by a replacement of the rock in and adjacent to the channelways; some was open filling. The conditions which brought about the deposition, and the reactions involved, are unknown. It is planned that these features be considered more fully in a later paper by the first named writer.

Tolman and Clark[45] point out that most ore solutions are probably combinations of colloidal suspensions and electrolytic solutions, and that colloidal dispersions of copper sulphides may be induced by hydrogen sulphide or other dispersing substances (especially in alkaline solutions), and flocculated by calcium carbonate. Precipitation by calcium carbonate offers an attractive explanation for the localization of the ores in the Chitistone limestone. The hypothesis finds support in the concentric and mammillary structures, occasionally observed in the ore, which resemble colloidal products, and some of it may have been formed in this manner. Clarke and Menaul[46] point out that colloidal solutions of sulphides may be so highly dispersed that they can penetrate the most minute fissures and pores, and their experiments

[45] ECON. GEOL., vol. IX., pp. 559–572, 1914.

[46] Clarke, J. D., and Menaul, P. L., "The Rôle of the Colloidal Migration in Ore Deposits," ECON. GEOL., vol. 11, p. 37, 1916.

show that copper in a colloidal solution can replace calcite. Whether the great ore bodies at Kennecott could be formed by this means is unknown, but if they could, many of the unusual features of those deposits would be understood. It would explain (1) the concentration of the copper in the limestone; (2) the lack of silicification or other alteration of the wall rock; (3) the remarkable purity of the ore; (4) the concentric structures which resemble diffusion structures; (5) the combination of open space and replacement; (6) the inability, displayed by the copper, to migrate far from the channelways; and (7) the lack of virility of the solutions which prevented them from penetrating through small gouge slips. The presence of small amounts of enargite and other minerals now or originally present would not be a stumbling block to the acceptance of the colloidal hypothesis, for the experiments of Clark and Menual demonstrate that they also replace calcite. Nor does its acceptance exclude precipitation by chemical reaction, from electrolytic solutions.

Primary or Secondary Origin of the Chalcocite.

General.—At the outset it must be admitted that the evidence concerning the hypogene (primary) or supergene (secondary) origin of the chalcocite is conflicting. Strong arguments can be advanced for and against both origins, and our knowledge of the general question is not sufficiently advanced to overthrow completely either hypothesis; certain features can be interpreted with equal force to apply to either origin. Field evidence, without corroborative microscopic study of polished specimens, has led to the assignment of an hypogene origin by Moffit and Capps,[47] and laboratory microscropic study of polished surfaces without corroborative field evidence led Tolman[48] to imply a supergene origin, though no direct statement to this effect was made. Graton and Murdoch,[49] who were the first to study Bonanza chalcocite by means of polished surfaces, thought that most

[47] *Op. cit.*, p. 82.
[48] Tolman, C. F., *Trans. Am. Inst. Engrs.*, vol. 54, pp. 402–435, 1917.
[49] Personal discussions.

of it was hypogene, but greater refinement of methods later revealed certain structures which led them to believe it to be mostly supergene. It is thus obvious that the correct interpretation can be reached only by correlating and properly weighing the different lines of investigation, such as field evidence, petrographic study, microscopic examination of polished surfaces, and experimental evidence. In none of these is our knowledge sufficiently complete to allow of conclusive deductions. In the final summary the weight given the various arguments will throw the scales one way or the other, but due to the different values given to the evidence by several investigators, a close agreement is hardly to be expected. In the following discussion of the different lines of evidence the writers beg tolerance of repetition in order to render clear the points at issue.

Experimental Evidence.—The Geophysical Laboratory investigations show that because Kennecott chalcocite contains over 8 per cent. dissolved covellite[50] it should display isometric etch patterns if formed above 91° C. Much of it does display octahedral partings (Plates III., IV., *A, B*), although "etched surfaces of some of the analyzed samples contain grains in irregular veins which etch like chalcocite (orthorhombic) and are thus shown to be the low temperature form. They may have formed above 91° and contain too little cupric sulphide to prevent their inversion, or they may have formed below the temperature of inversion."[51] Either explanation is possible. The twinned octahedral crystals (see page 63) are the strongest indication of isometric chalcocite. If it be established that the Kennecott chalcocite is isometric, it follows that it was formed above 91° C. and therefore hypogene in origin.

Mineralographic Evidence.—The experimental work demonstrates the conditions under which chalcocite may form, but microscopic examination of polished surfaces must be used to determine if the ore exhibits the features shown by the experimental work to be diagnostic.

[50] See pp. 62.

[51] Posnjak, Allen, and Merwin, *op. cit.*, p. 527.

The microscope reveals much chalcocite that strongly points to a replacement of bornite (Plate V., *B*), and some so absolutely free from residuals of former minerals as to suggest that it was originally formed in the limestone as chalcocite. The latter can, of course, be interpreted as the first stage carried to completion, and there is much to suggest that this may be the case. Etching demonstrates that most of the chalcocite has isometric patterns (Plates III., *A*, V., *A*, *B*). The isometric patterns may be interpreted as (1) partings inherited by replacement of an isometric mineral such as bornite, and (2) cleavage indigenous to isometric chalcocite. That secondary chalcocite does retain the cleavage of the mineral it replaces was first shown by Graton and Murdoch,[52] who described cleavage lines passing uninterruptedly from bornite to the replacing chalcocite. It is now a well-known occurrence.

Upon the correct interpretation of the isometric etch patterns lies the decisive clue to the primary or secondary origin of the Kennecott chalcocite for, if the first, the isometric cleavage is not diagnostic and merely proves that the chalcocite replaced bornite, and if the second, it was formed above 91° and is unquestionably primary or hypogene.

Tolman[53] presents strong proof to establish his positive statements that all the chalcocite replaces bornite and inherits its cleavages. He summarizes the mineral relations of the Bonanza deposit as follows:

First group: Bornite, klaprothite (klaprotholite) and galena; temperature of formation probably high.

Second group: Blue and white chalcocite of the first generation, secondary after bornite; temperature and source of solutions unknown.

Third group: Minerals formed progressively under conditions of increasing oxidation—second generation of white chalcocite → covellite and chalcopyrite → tenorite (and cuprite) → malachite → azurite; temperature "at about 0° C., as much

[52] *Op. cit.*, p. 58.
[53] *Op. cit.*, p. 408.

of the ore is frozen throughout the year. It is the result of the present vadose circulation, and the copper is migratory largely as malachite."

Tolman's mineral sequence is confirmed in a general way by our own work. No klaprothite or tenorite was encountered, however, and the extreme rarity of galena hardly entitles it to be mentioned with bornite. Limonite is not mentioned though fairly abundant, and much covellite was observed to be earlier than the chalcocite and among the first minerals to form. It is doubtful if azurite can be considered a replacement of malachite throughout all of the ore. Copper migrating as malachite by means of a frozen vadose circulation is rather surprising. Our microscopic examination of hundreds of specimens suggests that much of the chalcocite may have been derived from bornite, but not necessarily all of it.

On the other hand, some specimens suggest that the isometric structure is original. A specimen from the Mother Lode shaft collected in 1918 shows well-developed octahedral twinning, and also twinning on larger faces which are themselves twinned. After examining this specimen, Dr. Merwin states:[54]

The larger structure is octahedral, this grades off into the minute structure of the fresh chalcocite, even to the structure which etches on a polished surface. . . . That the structure here represented is pseudomorphic, I cannot believe . . . chalcocite formed at temperatures above about 93 degrees by replacing bornite or by any other process provided it contained about 10 per cent. or more of covellite in solution, would be expected to have just the structure which this Kennecott ore presents. . . . If actual unmixing (of the solid solution) takes place on lowering the temperature then new crystals of both covellite and chalcocite form and are thus contemporaneous. Or if pure chalcocite is being altered to covellite the surface of the chalcocite will first become a solid solution of chalcocite and covellite before actual crystals of covellite appear. From this saturated chalcocite, crystals of covellite will grow during further alteration and the two sets of crystals thus resulting (that is the covellite and the saturated solid solution) will be essentially contemporaneous. Of course, there may be covellite formed later from surrounding aqueous solutions. If the alteration and recrystallization take

[54] Merwin, H. E., letter from Geophysical Laboratory, Washington, dated April 16, 1919.

place below the inversion temperature of chalcocite we would expect orthorhombic chalcocite to be found in contact with the covellite; above this temperature isometric chalcocite would be expected. In the polished specimen which I have just examined the minute octahedral etch pattern can be seen in the chalcocite practically touching the covellite in places, and no orthorhombic pattern was seen.

Dr. Merwin's examination of the specimen strongly suggests an original octahedral structure. It is also significant that the octahedral partings of the artificial chalcocite formed above 91° C. yield etch patterns on the polished surface similar to the etch structures of the Kennecott chalcocite.

The specimen just described yields the most diagnostic evidence of all the microscopic examinations of the Kennecott specimens. Most of the microscopic evidence previously presented shows that the isometric etch patterns of the chalcocite cannot themselves be considered conclusively diagnostic of high temperature formation, therefore, of either the supergene or hypogene origin of the chalcocite, but this specimen strongly suggests an original isometric structure of the chalcocite, which in turn means its formation above 91° C. and by hypogene solutions.

Field Evidence.—It is obvious that secondary enrichment is impossible under present climatic conditions at Kennecott. It is also unlikely that any was associated with the oxidation now prominent throughout the deposit. The oxidation is limited for the most part to fractures upon which the chalcocite shows no dependence. It also causes alteration of the previously formed chalcocite.

The period during which the oxidation is considered to have been formed and particularly the one of mature development preceeding it, offered conditions that would have been favorable for any secondary enrichment to take place. Also, if the ore bodies extended up to the then existing surface on their present flat dip, a large amount of ore would be subject to oxidation and solution, for reprecipitation as secondary sulphides, because a lowering of 100 feet vertically would release 200 feet of ore. The field conditions were thus favorable for secondary enrichment on a large scale to take place. The presence of chalcocite

of unquestioned supergene origin in the bornite nodule (page 40) shows that secondary enrichment can take place in limestone, although the alteration in this case is on a small scale.

Opposed to the supergene origin of the chalcocite are the following arguments, based on field evidence:

1. There is no actual field evidence whatever (apart from microscopic or chemical evidence) to point to downward secondary enrichment, except that which has just been mentioned.

2. There is no distinct zonal arrangement, of oxidation, secondary sulphides, and primary ore, usually found in any deposit where secondary enrichment has taken place. There is only one zone of sulphides, with partial oxidation scattered all through it.

3. There is an absence of coatings of chalcocite or sooty chalcocite on other minerals, such as occurs in practically every deposit that has been secondarily enriched. If the deposit had undergone enrichment to the completeness required to account for the overwhelming proportion of chalcocite, it is difficult to understand how areas of enargite should remain absolutely fresh, without even a thin coating of chalcocite on the outside. One exception occurs, above the 100 level and near the surface of the Jumbo, where, in a shear zone a little surface water drips for part of the year, sooty chalcocite coats some enargite. It resembles the usual secondary enrichment. This exception, where clearly defined secondary enrichment does occur, suggests a different origin for the rest of the chalcocite.

4. If the chalcocite be attributed to descending waters, it implies the movement of large quantities of copper sulphate waters through the ore and adjacent limestone. Limestone has been found in other places to inhibit the formation of secondary chalcocite. It has been established from chemical and geological data that when copper sulphate solutions meet calcium carbonate, they lose their copper content by forming carbonates and basic sulphates of copper. Thus copper sulphate solutions, which journeyed considerable distance through limestone, would not have any available copper to form secondary copper sulphides.

The absence of malachite, azurite, or basic sulphates in the limestone walls, unconnected with sulphides, and especially along the little veinlets of chalcocite isolated in limestone, is a strong argument against the formation of the chalcocite from descending copper sulphate solutions.

5. If descending solutions produced the chalcocite, the limestone should show evidence of acid attack or of attack by ferric sulphate. Although the enrichment of bornite produces comparatively little acid, the great quantities involved, if all the chalcocite were formed in this way, would seem to have been sufficient to have produced a pronounced effect on the limestone walls. It should be pointed out, however, that Zeiss, Allen and Merwin[55] established an equation by which bornite may alter to a mixture of chalcocite and covellite with the production of no sulphuric acid, as follows: $Cu_5FeS_4 + CuSO_4 = Cu_2S + 2CuS + FeSO_4$. There is not sufficient covellite in the ore, however, to explain the formation of chalcocite by this equation, although if it were invoked to account for the proportion of covellite that does exist, it would mean that less acid would be formed than by the usual equations.

The only alteration of the walls is a slight amount of sandy limestone which occurs in but a few places. Its absence is an argument against the formation of chalcocite having taken place by descending solutions.

6. With the assumption of secondary enrichment, the replacement of such large masses of bornite by chalcocite, through the agency of descending solutions, would involve the release of a great quantity of iron, as sulphates. In neutral solutions, such as those in a carbonate rock, limonite would form readily if mild oxidizing conditions were encountered; if the iron remained in the ferrous condition reaction with the wall rock might be expected to yield siderite. The limonite in the deposits is insignificant in amount as compared to that which would be expected if the chalcocite were a supergene replacement of bornite. Further, the distribution of limonite suggests that it is largely a

[55] *Op. cit.*, p. 481.

product of later oxidation and connected with the destruction of the present ore and not with its formation. Siderite has not been observed. These considerations offer objections to a supergene process involving transportation of much iron through limestone in the form of soluble sulphates.

7. No change in the character of the minerals or the proportion of chalcocite takes place with increased depth; in secondarily enriched ores there is usually a gradual change from supergene to hypogene minerals.

8. Several blind veins occur in the mines, the upper parts of some of which do not come within 1,000 feet of the surface, and the character of ore and proportion of chalcocite in them is exactly the same as in the veins which outcrop. Also, there is no difference in upper and lower parts, and no oxidized zone lies above them. Such would not be expected if the chalcocite were formed by descending solutions.

9. In the main veins the chalcocite pinches out upwards, normal to the stratification, into barren limestone, and extends down the dip to unknown depth, so that from the 200 levels downward (see Fig. 6) no outcrops or zones of oxidized ore lie vertically above them. Therefore, the chalcocite in them could not have been formed by vertically descending waters. It is difficult to understand how any descending solutions could have produced the chalcocite in the tips of the inverted wedge-like veins unless the waters be considered to have moved almost laterally, which seems improbable.

A summation of the field evidence shows that it strongly favors a hypogene origin for the chalcocite, and that there is no direct evidence supporting a supergene origin, though in past geologic times conditions did exist which were suitable for secondary enrichment to have taken place.

Discussion of Evidence.—The microscopic evidence shows that an important part of the chalcocite exhibits features which may be considered an indication of replacement of bornite. If such be the case the chalcocite is later than the bornite. It does not necessarily follow, however, that the chalcocite must have

been formed as a result of descending solutions, even though the occurrence of almost identical relations between chalcocite and bornite in deposits of unquestioned secondary enrichment, does suggest a supergene origin for the Kennecott deposits. A replacement of bornite by chalcocite, only, is indicated, and this may have taken place either by descending solutions or by the final product of hypogene solutions. The field evidence strongly favors the latter. Such an origin for the chalcocite involves no overthrowing of established processes, except a customary tendency to regard as supergene all chalcocite which replaces bornite. No conclusive reasons are known to the writers why chalcocite cannot replace bornite by means of hypogene as well as supergene solutions. The hypogene replacement of pyrite by bornite, chalcopyrite, and other primary sulphides, also of chalcopyrite by bornite (Plate V., *C*), is a well-known and accepted fact. The hypogene replacement of bornite by chalcocite may take place in the same manner.

The processes involved in the replacement of one set of sulphides by another, in primary solutions, however, are not known. Probably it involves in part the application of Weigel's solubility tables, in which a sulphide in solution, of less solubility replaces one already formed, of higher solubility. Since iron and iron-copper sulphides are more soluble than copper sulphide, the tendency would be for chalcocite to replace bornite or other iron-bearing sulphides. This applies equally well to secondary or to primary solutions. That the replacement of bornite by chalcocite may have taken place by hypogene solutions is further supported by the finding of considerable chalcocite which shows no evidence of having replaced other minerals, but is strongly suggestive of having been originally deposited as such. In the specimen from the new shaft of the Mother Lode Mine there are relations suggesting graphic structures between bornite (primary) and chalcocite, which have been interpreted in some cases as typical between minerals of primary ore. It is reasonable to suppose that deposition from hypogene solutions would not be uniform, especially if derived as previously suggested, and that

from certain parts of the solutions more iron-containing minerals might be deposited than from others. Where other parts of the solutions meet such iron-bearing sulphides, they being of greater solubility, would be replaced by chalcocite; but where such sulphides are not encountered chalcocite would be deposited directly. Thus, chalcocite of both replacement origin and direct deposition might be formed in the same deposit. The process would not be unlike that which has taken place in most ore deposits where primary bornite or chalcopyrite has been deposited, in part by replacement of primary pyrite, and in part without replacing it.

That the isometric structures of the chalcocite (Plate III., *A*) may be inherited by replacement of bornite, would appear to invalidate the diagnostic criteria that might be applied from the experimental investigations of the Geophysical Laboratory. But chalcocite which has apparently replaced enargite also exhibits isometric structures. In these cases the isometric structures could not have been inherited,[56] and suggest chalcocite formed above 91° C. Also, in Plate V., *A* and *B*, malachite has developed along triangular isometric structures in the chalcocite, but along curved, irregular courses in the bornite. If the triangular isometric structure of the chalcocite be inherited from replacement of the adjacent bornite, should not the bornite also show the alteration to malachite in triangular patterns instead of curved lines? The fact that it does not, suggests that the isometric triangular pattern of the chalcocite is due to its having been formed above 91° C.

If replacement of bornite be considered as having given the chalcocite isometric structure, it seems strange that other chalcocite, also a replacement of bornite, should exhibit, not isometric but orthorhombic structure (Plate III., *C*). The latter is usually considered to be indigenous to chalcocite, and why might not the former also be considered indigenous rather than inherited? The orthorhombic structure cannot be inherited from bornite, for bornite is known only in the isometric form. Although it is

[56] Unless by some chance the chalcocite may possibly have replaced bornite associated with the enargite in replacement relations.

possible that bornite may have another crystallographic form, none has yet been found experimentally, and natural bornite has never yielded any other crystallographic structure than the isometric. The explanation as given by Posnjak, Allen and Merwin,[57] that the orthorhombic chalcocite may have been formed above 91° and contained too little covellite to prevent its inversion, seems a simpler and more direct one.[58] It is a rule that deposition from mineralizing solutions is not uniform, and it would be expected that in places chalcocite would contain over 8 per cent. covellite, and in other places less, thus allowing both the isometric and orthorhombic forms to persist. If the possibility that the isometric structure of the chalcocite was inherited, be excluded, the conclusive criteria established by the Geophysical Laboratory can then be applied to the Kennecott chalcocite to show that it was formed above 91° C., which also means that it is hypogene chalcocite. The evidence offered by the Mother Lode shaft specimen and the conclusions of Doctor Merwin regarding it show that, in this specimen at least, the isometric structure is in all probability original. Although the evidence from this one specimen cannot correctly be applied to all the isometric structures, it is, nevertheless, a strongly suggestive argument that the other isometric structures were formed the same way, and that the geophysical criteria can be applied.

The large amount of dissolved covellite in the Kennecott chalcocite (or the high sulphur content) also suggests a high temperature of formation. Posnjak, Allen and Merwin[59] produced solutions of covellite in chalcocite, down to 80° C., although the solution was more complete with higher temperatures. No solution was obtained at room temperatures, and such solid solutions

[57] *Op. cit.*, p. 527.

[58] In arguing for an indigenous rather than inherited isometric structure for the Kennecott chalcocite, the authors by no means intend to exclude all isometric structure from being inherited, as its occurrence has been conclusively proved by Graton and Murdoch, and numerous examples of it are familiar to the authors. Their contentions apply only to the Kennecott chalcocite.

[59] *Op. cit.*, 506.

have not been found in chalcocite definitely known to be supergene.

Aside from all discussion of evidence, the fact stands forth clearly that the Kennecott deposits show characteristics different from all deposits of unquestioned secondary enrichment by descending solutions.

Conclusions.—The general discussions of the different lines of evidence indicates rather clearly a hypogene origin for the chalcocite. The field evidence strongly suggests it and offers no opposing evidence, though it does show that certain conditions did exist whereby enrichment might have taken place. The microscopic evidence offers much in favor of a hypogene origin and nothing demonstrating a supergene origin. That much of the chalcocite replaces bornite is shown by the microscope, but this does not indicate a supergene any more than a hypogene origin. The experimental work of the Geophysical Laboratory offers diagnostic criteria applicable to the origin of chalcocite, and the arguments given above indicate that it can in all probability be applied to indicate a hypogene origin for the Kennecott chalcocite. The authors thus conclude, after a careful examination of the different lines of evidence, that practically none of the Kennecott chalcocite has been formed by cold descending solutions, but that it is the result of heated hypogene solutions;[60] part of the chalcocite having been formed by replacing earlier sulphides, part formed directly in solid solution with covellite, and part having been deposited as chalcocite.

SUMMARIZED CONCLUSIONS OF ORIGIN OF ORE DEPOSITS.

Subsequent to the conformable deposition of the Chitistone limestone upon the Nikolai greenstone, the formations were folded into a large anticline, upon the flanks of which were superimposed minor synclinal troughs, or possibly monoclines. The formation of the latter was accompanied by rupturing of the brittle limestone, giving rise to wedge-shaped fissures, by a

[60] A different interpretation of the origin of the chalcocite is held by Professor L. C. Graton, who will later discuss the subject from another viewpoint.

sliding of the beds over each other, and to separations along bedding planes. The openings thus formed were the loci for copper deposition which took place chiefly by replacement of limestone and adjacent to the openings, and to a minor extent by filling the open cavities.

The solutions are considered likely to have been meteoric waters which had their temperature raised within the earth, probably by contact with rocks heated by intrusions of porphyry magmas, or by contact with the magmas themselves. The possibility of the solutions having been direct emanations from the porphyry magma cannot, however, be eliminated. The warmed solutions then searched the copper and the small quantities of other metals out of the greenstone, the latter rock having obtained its copper content at, or shortly after, the time of extrusion. The warmed copper-bearing solutions circulated through the greenstone and deposited a small part of their load in the occasional small fractures or other openings they encountered, thus giving rise to small, irregular, and widely scattered deposits in greenstone. In a few places the solutions penetrated into the Chitistone limestone and encountering fractures and other openings in this congenial host rock, deposited their load in such concentration as to give rise to the Kennecott ore deposits. Where the openings in the limestone were few and small, or where the copper content of the solutions was low, minor deposits were formed, such as are widely scattered in the limestone near the greenstone contact. The relatively great concentration of copper in the limestone as compared with that in the greenstone is believed to be due largely to the physical and chemical differences of the two rocks; the limestone being more readily replaced and containing larger and more continuous fractures, whereas the greenstone offered no large or continuous openings and did not react readily with the mineralizing solutions.

It is believed that all of the sulphide minerals were deposited at this time by the primary solutions; the rarer sulphides being deposited first, and covellite, chalcopyrite, and bornite at about the same time or slightly later. The chalcocite deposition has in

large part taken place by replacement of bornite and other previously formed sulphides, but in many cases it seems to have been deposited directly without replacement of other sulphides. It is believed that the evidence, though not absolutely conclusive, is sufficiently strong to indicate a primary or hypogene origin for the chalcocite, and that if all the arguments favoring its hypogene origin were to be placed in one pan of a balance scale, and all favoring a supergene origin be placed in the other, the former would overwhelmingly outweigh the latter.

At a later period the region was eroded to a state of maturity, and conditions were made favorable for oxidation and any enrichment to take place, provided the ore deposits came within reach of oxidizing processes. Still later, under rejuvenated erosion, deep valleys were cut and Kennecott spur was rapidly lowered. The ore deposits were partially converted into carbonates of copper; small amounts of limonite and oxidation products of arsenic were formed. The oxidation extended to the greatest known depths of the deposit and is no more complete nearer the surface than at greater depth. In no place now existing is it complete, although it is greater along channelways than in unfractured areas or in massive ore. The oxidation gives the impression of having been produced by fairly rapidly moving waters, confined largely to channelways, and part of a deep circulation which sought outlet to the deep valleys below. With the exception of a negligible amount of sooty chalcocite found in the uppermost working of the Jumbo Mine, and possibly the chalcocite in the nodules, no secondary sulphides appear to have been formed at this time.

Oxidation was arrested with the advent of the Glacial Period by the freezing of the groundwaters and they have remained frozen until this day. Oxidation since then has been negligible; none having taken place underground, and that on the surface consisting only of a thin tarnish.

Mechanical erosion of the ore deposits has continued actively through the Glacial Period up to the present. During part of

the Glacial Period the accumulation of disintegrated ore débris from the Bonanza deposit, along with ice, gave rise to the Glacier ore body. On the other side of the slope the breaking down of the limestone and the contained ore deposit formed a talus slope rich in copper, giving rise to the slide ore bodies.

YALE UNIVERSITY,
NEW HAVEN, CONN.

THE RELATION OF OIL POOLS TO ANCIENT SHORE LINES.

PRELIMINARY PAPER.

WILLIAM F. JONES.

INTRODUCTION.

There is an undoubted tendency in recent literature on oil accumulation away from the generally accepted "structural" theory. Not only is this tendency noticeable in the literature, but it has been brought to the writer's attention in talking with oil geologists, who are actively engaged in commercial work in the oil fields.

The Anticlinal, or "structural," theory has gone from the simple, in its early conception, to the complex in the most recent paper by Clapp.[1] In its earliest stages the theory explained the accumulation of oil on simple flat anticlines and all complicated structures, such as produce oil in California, were condemned as unfavorable. On the other hand in Clapp's last structural classification[2] of oil pools, oil is shown to occur associated with every possible type of structural deformation. It has occurred to the writer that this fact alone is a grave weakness in the "structural" theory.

Underlying the "structural" theory, regardless of structural type, lies the postulate that oil migrates considerable distances; up the dip if water be present, down the dip if water be absent; in each case to the water surface or until further migration is impeded by the pinching out of the "sand," closed fault plane, or other obstruction. This simple process of accumulation undoubtedly takes place where conditions are right as regards size of pores in the sand, viscosity of the oil, and sufficient dip of the

[1] F. G. Clapp, "Revision of the Structural Classification of Petroleum and Natural Gas Fields," *Bull. Geol. Soc. Am.*, vol. 28, 1917, pp. 553–602.

[2] *Idem.*

roof of the porous bed. Just what the necessary dip is for any set of conditions of porosity and viscosity is unknown. That there is a limiting angle of dip is evident and this point is admitted by Clapp[3] in the structural classification in that there is inserted what is called a "subaclinal" structure where there is "too slight a dip to fully separate the oil and gas from the accompanying water."

As early as 1909, Munn[4] doubted the lateral migration of oil due to relative specific gravity in regions of low dip and specially mentioned the oil pools of the "100 Foot" sand in the Sewickly quadrangle of Pennsylvania. Recently McCoy[5] has shown that, experimentally at least, oil will not migrate up even a considerable dip even when water is circulating through the porous bed in an up-dip direction.

In a recent discussion of a paper by Woodruff[6] on Petroliferous Provinces, Schuchert[7] classifies areas, as far as oil content is concerned, into three groups, viz., (1) The impossible areas for petroliferous rocks, (2) possible petroliferous areas and (3) petroliferous areas. Under the last heading Schuchert says:[8]

> All marine strata that are, roughly, within 100 miles of former lands; here are more apt to occur the alternating series of thin- and thick-bedded sandstones and limestones interbedded with shale zones.

And again in the same paper[9]

> Muddy waters with the finest of silts and not too much agitated by currents or winds are the places where the hydrocarbons naturally may accumulate. . . . The petroliferous deposits are accumulating today in greatest amount in the shallow waters bordering the lands rather than in greater depths.

[3] *Idem*, p. 560.

[4] M. J. Munn, "Studies in the Application of the Anticlinal Theory of Oil and Gas Accumulation," ECON. GEOL., Vol. 4, 1909, pp. 141–157.

[5] A. W. McCoy, "Notes on Principles of Oil Accumulation," *Jour. Geology*, vol. 27, 1919, pp. 252–262.

[6] E. G. Woodruff, "Petroliferous Provinces," *Bull. Am. Inst. Min. and Met. Engrs.*, No. 150, June, 1919, pp. 907–912.

[7] *Op. cit.*, No. 155, Nov., 1919, pp. 3058–3070.

[8] *Idem*, p. 3060.

[9] *Idem*, p. 3064.

The suggestion is evident in Schuchert's discussion that the favorable places for accumulation of bituminous material are lagoons and embayments along coasts and the importance of the delineation of ancient shore lines in connection with oil developments is emphasized.

The writer agrees with McCoy that, except under special conditions, there is no wide lateral migration of oil in the process of its accumulation and that oil pools have only slight and indirect relationship to so-called "structures" such as terraces, anticlines and domes in regions of low dip. The writer also suggests that there is a great deal of evidence to show that the individual oil pools of the Appalachian and of the Mid-Continent regions do not conform in general to structural deformations nor do the pools result from migration due to dip of the beds but bear a close relationship to the configuration of the ancient coast lines in each case. A general summary of the evidence will be presented at this time.

APPALACHIAN REGION.

In the time of Lesley and the early oil developments in Pennsylvania, anticlinal axes were indicated on the maps by straight lines generally parallel with a strike of about N. 30° E. Oil pools, as they developed, showed, for larger pools, a general elongation in the same general direction. This apparent parallelism of structural axes and pool elongation naturally gave rise to the assumption of a direct relationship. Drilling started always on an anticline and if the well was productive new wells were located either side in this prevailing direction. It was undoubtedly in the assumption of this relationship between axes of anticlines and pools that the anticlinal theory had its inception.

Work of more recent years shows the structural axes of this region to be very sinuous and wavy lines and by no means continuous for great distances. Far more regular and systematic is the direction of elongation of the major oil pools (see Fig. 13).

In many cases a single oil pool crosses several anticlines and the intervening syncline. Among these may be mentioned the McDonald field in Washington and Alleghany counties, and the Crows Run pool in Beaver County, Pennsylvania.

Another point worthy of note is that in the Foxburg quadrangle in Pennsylvania, the well-defined pools exhibit the same direction of elongation as elsewhere in the region and in this district no defined structural axes can be delineated.

Again, when the entire Pennsylvania region is considered with reference to the oil pools in any one sand, a very definite align-

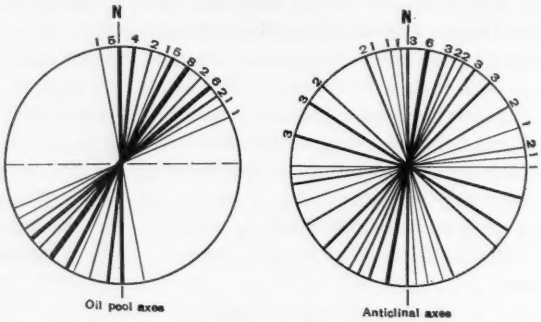

FIG. 13. Showing strike of long axis of major oil pools and strike of anticlinal axis in the Foxburg, Burgettstown, Carnegie and Sewickley quadrangles, Penn.

ment of pools is noted, this alignment bearing no relation to the structural axes traversing the region. The oil pools of the "100-Foot" sand show this alignment to a very noticeable degree, especially in the Sewickly quadrangle.

In the Pennsylvania region there is another feature in the structural makeup which has escaped notice in its relation to the soil accumulations. An uplift to the north causes all the structure contours to generally traverse the region from east to west rather than run generally parallel to the structural axes. In many cases the element of pitch is far more potent than the element of folding in the resultant dips of the beds. If gradient has caused migration and accumulation, then the prevailing direction of elongation of the oil pools should more nearly parallel the East-West trend of the structure contours. The only major pool which does show any approximation to alignment with the contours is the Washington-Taylorstown field in Washington County.

The suggestion is made that the position of the oil pools in this region is largely determined by conditions of deposition and that the alignment and elongation of the pools is significant of lagoonal conditions along a coast line at the time the bituminous shales from which the oil was derived were being deposited and that the present position and shape of the oil pools is largely due to the position and shape of the supply area of the lagoonal deposit; such deposit being either directly below or directly above the pool, the oil having been transferred vertically by the capillary force of water, practically no lateral migration having taken place.

MID-CONTINENT REGION.

Only the oil-bearing region of Oklahoma will be considered in the present paper. The general structure of the region is homoclinal, with a prevailing westerly dip. Bulges in this prevaling structure give rise to isolated domes and anticlines. These "structures," in contrast to the Pennsylvania region, are not continuous or uniform and the structural axes are short and without any prevailing strike. Far more regular in their delineation are certain fault zones such as are found extending in a North-South direction through part of the Osage Indian Reservation.

The arrangement of oil pools in this region bears a close resemblance to Pennsyvlania. The major pools are generally elongated in a North-South direction and developments seem to indicate a rough alignment of the pools, at least those in the Bartlesville sand.

In the Osage Indian Reservation, where the pools seem to be generally limited in area, the relation of these pools to structure, in most cases, is not apparent. Many of the pools are "off structure" and many "favorable" structures are barren. There is apparently a wide discrepancy between the position of known oil pools relative to structural conditions as indicated on the maps and the recommendations for development in the texts in the recent U. S. Geological Survey Bulletin on this region.[10]

The larger pools of Oklahoma, with the exception of Cushing

[10] Bull. 686, U. S. Geological Survey, issued in parts.

are in unfavorable structural positions. For example, the Glenn pool, while ascribed to structural accumulation in the literature, lies on a westerly dipping unit with only minor cross pitching folds. If the oil has migrated laterally to its present position there is nothing to prevent its further migration to the East. The same may be said of the Bartlesville area and of the Nowata pool. Cushing is the one exception of the major pools, occupying a well-defined triple dome, but the question arises as to whether the structure, in this case, caused the accumulation or whether the structure has merely happened to have been imposed over, or under, an area of rich bituminous deposit, the consequent fracturing due to the deformation having permitted a freer transfer of oil, for this district is certainly unique in having three generally directly superimposed oil sands, each one of which has been prolific in oil production.

PRE-DEFORMATIONAL ACCUMULATION.

McCoy suggests[11] that the solid kerogens of the bituminous shales are converted to liquid hydrocarbons by pressure. If this is so it is not only possible but probable that much of this conversion took place prior to any deformation and during the compacting stage and when the present oil horizons were deeply buried beneath sea level.

It seems possible that the original accumulations of oil extended much farther east both in Pennsylvania and Oklahoma, each belt of pools corresponding to an ancient shore line and that deformation or compression destroyed the more easterly accumulations in the same manner that it increased the fixed carbon content of the coal deposits. Hence we have the rule of fixed carbon content to go by in explorations for oil, which seems to be applicable very generally. As corroborating this we have in Pennsylvania the well-defined gas belt, without oil, lying east of the oil belt, the two overlapping to a considerable extent.

We thus have the suggestion that, in so far as the Paleozoic formations of Pennsylvania and Oklahoma are concerned, de-

[11] *Op. cit.*

formation is a destructive, rather than a constructive factor in oil accumulation.

CONCLUSIONS.

The foregoing notes lead to the following conclusions in so far as the Pennsylvania and Oklahoma regions are concerned:

1. Oil has been forced out of the fine bituminous shales by the capillary action of water.

2. The oil has accumulated in nearby porous beds either by the porous bed or beds being in direct contact with the source of supply or by fracturing, as suggested by McCoy, if the two are not in contact.

3. No wide lateral movement of oil has taken place and the present position and shape of oil pools closely conforms to the underlying or overlying source of supply.

4. The areas of supply are lagoonal areas close to and generally parallel with the coast line at the time of deposition.

5. Pools generally occur in alignment corresponding to the coastal lagoonal areas, each line of pools corresponding to succesive shore lines, with generally barren belts intervening.

6. Larger pools are elongated to correspond to the prevailing elongation of the larger basins of accumulation.

7. Certain types of structure are favorable for large initial yield of oil, since domes, if they happen to exist in a productive area, act as pressure traps for gas.

8. Oil pools, in Pennsylvania and Oklahoma, may be largely of pre-deformational accumulation.

9. A detailed study of paleography and a delineation of ancient shore lines would prove of considerable value in directing the major drilling developments.

10. There may be extensive areas of favorable oil land in regions condemned at present because of the lack of so-called favorable structure.

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THE OCCURRENCE OF BINDHIEMITE AS AN ORE MINERAL.[1]

EARL V. SHANNON.

Bindhiemite, a hydrous antimonate of lead of somewhat variable composition has commonly been regarded as a comparatively rare mineral. For some time past, the writer has been engaged at intervals in the examination of specimens of this mineral with a view to learning definitely its mineralogical nature and chemical composition. Results of analyses seem to indicate that there may be two minerals included under the name bindhiemite but discussion of the constitution of the species will be reserved for a more strictly mineralogical paper to be published in the Proceedings of the U. S. National Museum. The investigations have shown bindhiemite to be much more common than is generally believed and its widespread occurrence in oxidized lead-silver deposits of the western states is worthy of some attention from students interested in the chemistry of oxidation and secondary enrichment. Below are given descriptions of bindhiemite bearing ores from a number of new localities, with references to those previously described.

In the Coeur d'Alene District, Idaho, great bodies of oxidized ore have been mined from the upper portions of silver-lead veins in quartzite. The oxidized ores consisted for the most part of cerussite and limonite with smaller amounts of anglesite, pyromorphite, plattnerite, and native silver. A common constituent of the oxidized ores of all of the larger mines of the region was a soft, ocherous material of a canary yellow color, which except in its brighter tone of color, looked very much like the ocherous limonite which was very abundant in the ores. The miners recognized this mineral and commonly referred to it as "chlorides" and

[1] Published from the Division Applied Geology, U. S. National Museum, by permission of the Secretary of the Smithsonian Institution.

regarded it as indicating rich silver values in the oxidized ore. Such soft yellow material was recognized by Ransome and described as massicot.[2] The present writer made some preliminary blowpipe tests on this material and obtained no distinctive reactions for antimony, which results led to the statement in an earlier paper[3] that bindhiemite did not occur. Later more thorough examination established the presence of antimony in all specimens of this yellow substance from every oxidized ore body in the district. No specimen of genuine massiot is now known to have been found in the region. In the Caledonia, Hercules, and Mammoth mines, hundreds of tons of ores in which bindhiemite was a conspicuous constituent have been mined, and in much of the ore of the Caledonia mine the valuable metals were contained in this mineral alone, masses of nearly pure bindhiemite several feet in diameter at times being exposed in the oxidized ores and having the same position and attitude as masses of tetrahedrite in the unoxidized portions of the vein. Sulphantimonites other than tetrahedrite are rare in this district and the bindhiemite seems to represent a pseudomorph in most cases after tetrahedrite and to have formed by reaction between lead compounds in solution and the antimonial mineral in place. That a reversal of this relationship is possible is shown by occasional masses of galena crusted with bindhiemite and by masses of bindhiemite having the granular structure and cubic cleavage of galena preserved. The mineral has been especially prominent also in ores of the Last Chance, Sierra Nevada, Blackbear, Poorman, Morning and numerous other mines in this district. The material usually is a little less rich in silver than the tetrahedrite of the same mine. In the Hypotheek mine the bindhiemite is derived from a silver-free famatinite and carries little silver. A specimen of earthy compact bindhiemite of a bright yellow color associated with limonite and cerussite from this mine, upon analysis yielded the following results:

[2] Ransome, F. L., and Calkins, F. C., "Geology and Ore Deposits of the Coeur d'Alene Mining District, Idaho," Prof. Paper U. S. G. S. No. 62, p. 94.

[3] Shannon, E. V., "Secondary Enrichment in the Caledonia Mine, Coeur d'Alene District, Idaho," Econ. Geol., vol. VIII., No. 6, September, 1913, p. 565.

TABLE I.

BINDHIEMITE, HYPOTHEEK MINE, IDAHO.

	Per Cent.
Insoluble	2.28
PbO	53.48
Sb_2O_5	36.54
Fe_2O_3	3.84
CO_2	.60
H_2O — 110° C.	.30
H_2O + 110° C.	3.27
Total	100.31

The above analysis may be interpreted as a mixture of the following mineralogical composition:

	Per Cent.
Limonite	4.49
Cerussite	3.64
Bindhiemite	89.83
Insoluble (quartz)	2.28

Ocherous yellow bindhiemite carrying considerable values in gold occurs at the Loxley mine, South Mountain Dist., Owyhee Co., Ida. At a small mine near Boundary, Wash., lumps of a mineral resembling tetrahedrite occur surrounded by a crust of earthy yellow bindhiemite, imbedded in coarse galena. In the Elkhorn district, Mont., bindhiemite occurs sparingly with cerussite and calamine in oxidized ores of the Elkhorn mine. Ocherous bindhiemite occurs with galena cerussite and anglesite in quartz from the Modoc Chief Mine, Boulder District, Jefferson Co., Montana.

In South Dakota, ocherous bindhiemite occurs sparingly in auriferous quartz ore at the Durango mine, at Lead, Lawrence County. Specimens from Silver City show compact wax-like yellow to brown bindhiemite with a fibrous structure suggesting silicified wood, the structure being pseudomorphous after jamesonite from which the bindhiemite is derived.

In Utah bindhiemite occurs abundantly in the Park City district as a yellow to greenish impure alteration product of tetrahedrite as described by Boutwell.[4] Ordinary ocherous yellow

[4] Boutwell, J. M., "Geology and Ore Deposits of the Park City District, Utah," Prof. Paper U. S. G. S. No. 77, pp. 110–114, 1912.

bindhiemite occurs with impure cerussite at the Eureka Consolidated mine, Tintic District; coating galena at the Crescent mine, Gate Co.; Niantic Mine, Lucin Dist., Boxelder Co., with cerussite; Flavilla mine, Dry Canon Dist., Boxelder Co., with galena and linarite; and at the Hornsilver Mine, San Francisco District with cerussite.

In Nevada bindhiemite is of very widespread occurrence. Compact yellow lead antimonate occurs with galena, tetrahedrite, and malachite in ores of the Belmont and Highbridge mines, Philadelphia District, Nye Co. A red ocherous material from the Wamsley Mine, Mineral County, upon analysis yielded the following results:

TABLE II.

ORE, WAMSLEY MINE, NEVADA.

	Per Cent.
SiO_2	9.65
PbO	9.73
Sb_2O_5	8.86
HgS	46.59
AgCl	.10
Fe_2O_3	3.22
ZnO	19.94
H_2O	1.83
Total	99.92

This analysis may be interpreted as:

	Per Cent.
Quartz	2.27
Willemite	27.32
Cinnabar	46.59
Limonite	3.77
Bindhiemite	19.87
Cerargyrite	.10

The material is so fine grained as to appear homogeneous under the microscope. It seems not improbable that this peculiar mixture resulted from the oxidation of the mercurial variety of tetrahedrite. Analyses of three yellow bindhiemites from the same locality are given in the following table:

TABLE III.

	a, Per Cent.	*b*, Per Cent.	*c*, Per Cent.
Insoluble	3.63	4.97	4.32
Sb_2O_5	40.35	42.71	23.08
PbO	44.12	41.67	49.60
Fe_2O_3	5.22	4.01	18.72
H_2O	5.31	6.31	3.80
	98.63	99.67	99.52

Nos. *a* and *b* are hard, heavy, and corneous varying from clear yellow to brown in color. No. *c* is a soft pulverulent yellow ocher with streaks of limonite.

A specimen of hard corneous yellow to brown bindhiemite from Lovelock, Nevada, yielded upon analysis the following results:

	Per Cent.
Insoluble	6.32
Sb_2O_5	43.63
PbO	36.54
Fe_2O_3	4.30
H_2O	5.78
Total	96.57

Bindhiemite has also been noted as a yellow powder in ores from the Tipton Mine, Esmeralda Co.; and with cerussite in oxidized gold ore from the Rochester-Merger mine at Rochester, Nev. Fibrous woody lead antimonate, pseudomorphous after jamesonite or a related mineral, occurs at the Montezuma ledge, Humboldt County.

In New Mexico specimens showing ocherous bindhiemite associated with very pure massive cerussite and large crystals of linarite have been collected from the Stevenson-Bennett Mine, at Las Cruces.

In Colorado bindhiemite surrounds anglesite nodules at Christy Butte. Specimens collected by S. F. Emmons at Clinton, Custer Co., consist of soft yellow bindhiemite rich in gold and silver.

Specimens of pale yellow ocherous bindhiemite from San Bernardino Co., California, are indistinctly fibrous and are probably

pseudomorphous after jamesonite. Upon analysis this material was found to have the following composition:

TABLE IV.

BINDHIEMITE, SAN BERNARDINO CO., CAL.

	Per Cent.
Insoluble	2.93
PbO	40.53
Sb_2O_5	44.28
Fe_2O_3	3.28
H_2O	5.04
Total	96.06

From the foregoing it is apparent that bindhiemite is very widely distributed in oxidized ores, probably occurring wherever antimonial sulpho-salts have been subjected to surface weathering. The affinity of the oxy-acid of antimony for lead is very marked, lead-free antimony compounds rarely if ever remaining where lead was available. The reactions involved in the breaking down of antimonial sulphides are very imperfectly understood. That some antimony compound is carried in solution by cold sulphate waters is proven by the formation of such minerals as pyrargyrite in the zone of secondary sulphide enrichment, but the relative insolubility of antimony causes it to remain for the most part as insoluble compounds in the zone of weathering. It appears that of these insoluble end products bindhiemite is the most common.

U. S. NATIONAL MUSEUM,
WASHINGTON, D. C.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

RELATION OF OIL TO CARBON RATIOS.

Sir: The very interesting and instructive paper by Mr. M. L. Fuller which recently appeared in this journal,[1] wherein he applies to north Texas the carbon ratio principle first enunciated by Dr. David White[2] has naturally led to efforts to use the same criterion in other districts. The present discussion and accompanying map (Fig. 14) express an attempt to apply it in central and north Alabama. There is this difference between the two cases, however. North Texas is already an important oil field, and Mr. Fuller's communication serves both as a confirmation of the principle and as a basis for directing further exploration in that region. Up to date, however, no oil and very little gas has been produced in Alabama, so that the present map if it has any value at all will serve only in the latter capacity.

The references already given contain a fairly complete discussion of Dr. White's hypothesis, and repetition here is unnecessary. Briefly, the percentage of fixed carbon in the coals of a district (reckoned on a "pure coal" basis) serves as a criterion of the absence or *possible* presence of oil in that district, in commercial quantities, and of the quality of the oil, when found, as well. Dr. White places the "dead line," beyond which oil will not be found,

[1] ECONOMIC GEOLOGY, vol. 14, p. 536, 1919.

[2] *Trans. Wash. Acad. Sc.*, vol. 6, p. 189, 1915; *Bull. Geol. Soc. Am.*, vol. 28, p. 727, 1917.

at 65 per cent. of fixed carbon; Mr. Fuller finds that in north Texas the dead line is 60 per cent., while the bulk of the production there has come from regions showing percentages between 55 and 50. Since no production of oil has been made in Alabama, the isovolves (lines of equal fixed carbon) are merely

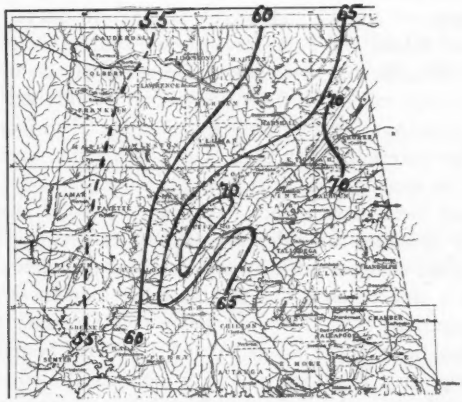

FIG. 14. Map of part of Alabama, showing lines of equal fixed carbon.

given, and the reader allowed to draw his own conclusions. In the judgment of the writer, however, commercial oil deposits will not be found to the east of the 60 line.

Only a couple of analyses could be found giving a percentage of fixed carbon below 55, and the corresponding line is therefore only indicated, as its course is somewhat uncertain. The 75 per cent. line is not drawn at all, in the absence of a sufficient number of analyses approaching that figure, but it would doubtless lie to the east of the 70. In the crystalline region still further east there are deposits of amorphous graphite associated with rocks containing Pennsylvanian fossils. These no doubt represent the end products of the metamorphism of coals, which gradually increases in intensity toward the east. A few analyses of carbonaceous

shales were found, but did not give results in harmony with those obtained from the coals.

The analyses consulted in the drawing of the isovolves number about 150, and were obtained from the records (mostly unpublished) of the Geological Survey of Alabama through the courtesy of the chemist to the Survey, Mr. R. S. Hodges; from the publications of the United States Geological Survey and the Bureau of Mines, and from some private sources. As would be expected considerable discrepancies were found in analyses of the same coals, made at different times and by different analysts. These are due to at least two causes. Samples taken from an outcrop differ materially from those under even a thin cover, and in addition the specifications governing the determination of volatile matter and hence fixed carbon have changed from time to time. Generally speaking the older the analysis the higher the fixed carbon, while analyses made by coal mine chemists likewise show as a rule a higher percentage for the latter than those made by disinterested analysts. Some discretion was necessary therefore in collating the analyses available, and it will not be difficult for anyone repeating the work to find an occasional analysis which does not fall within the region to which it belongs geographically. Since the percentages in the Cretaceous and later lignites to the south are all favorable to the accumulation of oil the map is confined to the Pennsylvanian area.

STEWART J. LLOYD.

UNIVERSITY OF ALABAMA,
UNIVERSITY, ALA.

SCIENTIFIC NOTES AND NEWS[1]

MOWRY BATES has moved his offices from the First National Bank Building to Suite 217, Okmulgee Building, corner Fifth and Boulder Streets, Tulsa, Oklahoma.

E. H. FINCH, geologist, has been appointed chairman of the Mineral Division, Land Classification Branch, U. S. Geological Survey, succeeding Mr. A. R. Schultz, who has resigned.

FRED B. ELY has accepted a position in the geological department of the Pierson Oil Company, and has his headquarters at Shreveport, La.

FRANK HESS and R. M. OVERBECK, of the U. S. Geological Survey staff, have gone to South America, to investigate various ore deposits in Bolivia, Chile and other South American countries. They will remain for six months or more.

DAVID WILKINSON has accepted the position of consulting engineer to the Consolidated Gold Fields Company of South Africa, succeeding C. D. Leslie.

CARL B. ANDERSON, who was formerly with the Illinois Geological Survey and the Gulf Oil Corporation, has joined the staff of Rogers, Mayer and Ball, of New York and Boston, who announce that their facilities for the examination and appraisal of oil properties will be extended.

W. J. MEAD has resigned as chief geologist for the E. J. Longyear Company of Minneapolis and will devote his time outside of

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

his duties as associate professor of geology at the University of Wisconsin, to his private consulting practice.

J. M. HILL, of the U. S. Geological Survey, has returned from a trip to the Colombian platinum deposits.

WILLETT G. MILLER has returned from England, where he was Canadian representative of the Imperial Mineral Resources Bureau.

L. C. GRATON has accepted a position with the Calumet and Hecla Mining Company, and will make a complete geological survey of the territory owned, controlled or managed by the interests in northern Michigan, comprising 23,000 acres. The work will probably require two years.

EDSON S. BASTIN's permanent address is now Rosenwald Hall, University of Chicago, Chicago, Illinois.

D. F. HIGGINS was demobilized from the Chinese Labor Corps of H. M. Forces in France, in May, 1919. He spent the summer in Spitzbergen and in November he went to northern Africa to undertake geological examinations for petroleum for S. Pearson and Son, Limited, London.

CHARLES W. WRIGHT, formerly of the U. S. Geological Survey, has returned to Sardinia and Rome, where he has offices as consulting mining engineer.

ERNEST W. MILLER has returned from the Orient and is now doing petroleum geology in St. Louis.

A. P. COLEMAN, professor of geology at Toronto University, has been made dean of that institution.

JOHN T. REID has left Nevada and is in New York for the winter on mining business.

W. W. J. CROZE, manager of the geological department of the Oliver Iron Mining Company, at Duluth, Minnesota, has gone to Brazil.

E. T. MELLOR has returned from London to the Rand.

WALDEMAR LINDGREN has returned to Cambridge after several weeks' absence in Utah and the South.

ADOLPH KNOPF has obtained leave of absence from the U. S. Geological Survey from February until June to occupy the position of Temporary Lecturer at Yale University, where he will teach the courses in petrography and petrology previously given by the late Professor Pirrson.

JOSEPH T. SINGEWALD, JR., professor of economic geology at the Johns Hopkins University, sailed for Peru to carry on some geologic investigations in the northwestern part of the country.

P. A. BALLARD, formerly geologist for the Midwest Refining Company, is now engineer for the Dakota Oil Company and the Norbeck Nicholson Company, and is continuing his private business as consulting petroleum geologist at Custer, S. D.

B. HUBBARD has resigned his position in the department of geology at Columbia University, and has accepted a position at Queen's University, Kingston, Ontario.

WILLIAM F. PROUTY has resigned his position as professor in the University of Alabama and chief assistant on the Alabama Geological Survey, and has accepted the professorship of Stratigraphical Geology in the University of North Carolina, at Chapel Hill.

COURTENAY DEKALB sailed recently from Brest to New York.

L. KEITH WARD is now secretary of the South Australian Department of Mines, succeeding F. C. Ward. L. Keith Ward will still continue in his position of Government Geologist and Director of Mines.

J. B. TYRELL, of Toronto, has gone to England, where his address will be 208 Salisbury House, London, E. C.

H. FOSTER BAIN is now in Rangoon, Burma.

F. P. MENNELL is making a geologic investigation of the Rhodesia Broken Hill Mine, in Rhodesia.

FRANK H. PROBERT, dean of the Mining Department of the University of California, has been in Arizona for a time, but has now returned to California.

WILLIAM HUFF WAGNER has resigned his position as geologist and chief engineer for the North Butte Mining Co. to join the technical staff of the Income Tax Bureau on Mines, at Washington.

ELLSWORTH BENNETT, who is in charge of the Tonopah School of Mines, recently made an examination of the La Toska Mine, near Oreana.

ANDREW W. NEWBERRY has opened an office at 66 Broadway, New York, for the examination of mining properties.

WILLIAM B. GOHRING, who was for fourteen years connected with the Calumet & Arizona Mining Company, has resigned as mining superintendent, and will engage in business for himself with headquarters at Tucson, Arizona. He was succeeded by E. E. Whitely, the assistant superintendent.

TUDOR G. TREVOR, Inspector of Mines in the Transvaal, is in London.

OSCAR H. HERSHEY has gone to Oatman, Arizona.

CHARLES F. WILLIS has become editor of the *Arizona Mining Journal*, published at Phœnix.

THE ARIZONA BUREAU OF MINES at Tucson, Arizona, through the resignation of Olaf P. Jenkins, is left without a geologist to carry on the growing geological research and field work of that state.

THE GEOLOGICAL SOCIETY OF AMERICA held its annual meeting in Boston, December 29–31. The meeting was fairly well attended and a large number of papers were presented. Among

those pertaining to economic geology, were: "The Ternary System Fe_2O_3—SiO_2—H_2O," by H. E. Merwin and E. Posnjak; "Experimental Chemical Data on Formation of Smithsonite," by T. L. Watson; "Contact Metamorphic Deposit, Mountain Lake Mine, Utah," by Austin F. Rogers; "New and Rare Contact-Metamorphic Minerals in Limestone," by A. S. Eakle; "Survey of Road Materials in New Hampshire," by J. W. Goldthwaite; "Carboniferous Salt and Potash Deposits of Eastern Canada," by Albert O. Hayes; "The Natural Gas Decline Curve," by Roswell H. Johnson; "Deep Drilling Results in Appalachian Oil and Gas Fields," by I. C. White, and "Geology of Ore Deposits of Kennecott, Alaska," by Alan M. Bateman and D. H. McLaughlin.

PETROLEUM GEOLOGISTS of New York City were invited by E. DeGolyer to attend a luncheon on December 16, at which an organization called "The Clinometer Club" was formed to bring them together from time to time. The first club luncheon, tendered by Dorsey Hager, was given on December 23. Those present were: W. A. Williams, V. R. Garfias, H. E. Boyd, G. E. Cheda, Ralph Arnold, Donald F. MacDonald, Arthur C. Veatch, Roderic Grandall, W. B. Heroy, Heath M. Robinson, Dorsey Hager, E. DeGolyer, Frederick G. Clapp, Albert D. Brokaw, L. G. Donnelly and James F. Kemp. The second club luncheon was given by W. A. Williams on January 6. Petroleum geologists who have not received invitations are invited to advise the secretary, E. DeGolyer, 65 Broadway, New York City.

HORACE V. WINCHELL addressed the local section of the A. I. M. E. at San Francisco on December 22.